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Analysis of Emerging Technologies and Trends for ADF Combat Service Support 2016

Ksenia Ivanova and Guy Edward Gallasch

Land Division
Defence Science and Technology Group

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ABSTRACT

Strategic planning is supported by an understanding of emerging trends and technologies. This report provides such a horizon scan for Combat Service Support (CSS). Global trends and the results of science and technology literature scans across seven domains (power and energy, transportation, robotic and autonomous systems, materials and manufacturing, sensors, information and communication technology, and health technologies) are presented. Technologies of interest are further assessed in terms of their usability, potential costs and comparison with the existing options. A comparison to the results of the scan of the previous year is provided, and previous recommendations updated. Finally, an analysis of emerging trends and technologies draws out new recommendations, including for ongoing horizon scanning activities to be combined with development and assessment of detailed concepts of employment for some maturing technologies that offer significant benefits for ADF CSS.

Produced by

Land Division
DST Group Edinburgh
PO Box 1500
Edinburgh SA 5111

Telephone: 1300 333 362

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Executive Summary

Strategic planning is supported by an understanding of emerging trends and technologies. This report follows on from previous horizon scanning studies for the Australian Defence Force (ADF) Combat Service Support (CSS) in line with Army Research and Development Requirements ARDR 16/0044 and 16/0054. This is done through scans of science and technology (S&T) literature as well as consolidated reports. Technologies of interest are further assessed in terms of their usability, potential costs and comparison with the existing options. The report covers seven technology groups based on previously developed ADF-tailored taxonomy: power and energy, transportation, robotic and autonomous systems, materials and manufacturing, sensors, information and communication technology (ICT) and health technologies. The scope of the report covers technologies that are directly relevant to logistic operations, as well as those that are likely to have wider impacts on military operations.

Global trends: The current meta-trends are characterised by accelerating technological change and digitisation of most aspects of life, with associated concerns around cyber-security, privacy and automation of jobs. Western societies have witnessed wide-spread disenfranchisement with the established government and economic models in the context of continued economic instability, urbanisation and ageing population. Climate change concerns include an increase in the rate and severity of natural disasters, mass migration, resource shortage, and loss of coastal infrastructure.

These trends are likely to affect the nature of military operations as well as the characteristics of potential adversaries. Easier access to sophisticated technology by non-state actors makes the terrorist threat more widespread and harder to detect. Cyber-attacks and espionage are becoming a standard part of national toolkits for exerting influence in many countries. Use of unmanned systems and artificial intelligence (AI) at the tactical level is likely to accelerate the pace and lethality of engagements, while developments in hypersonics will extend their speed and range. Climate change effects may entail additional requirements for humanitarian assistance, stabilisation and border security operations. Furthermore, these operations are likely to be more dispersed and disaggregated, develop faster and take place within civilian settlements in urban, littoral or amphibious environments.

Power and energy: Developments in power and energy are characterised by a global shift towards cost-effective renewable energy systems. Hybrid technologies such as hybrid generators represent an intermediate stage in this trend and are already used in military operations, as are portable and flexible solar panels. Research continues into energy scavenging for small devices, hydrogen fuel cells and wireless charging. Battery designs continue to evolve and are closely watched as enablers for several other industries.

Transportation: Apart from autonomous and semi-autonomous vehicles, developments in transportation technologies include new container designs and novel airless tyre designs. Work continues in improving the precision of air-drop technology, and a resurgence has occurred in use of airships.

Robotic and autonomous systems: Use of unmanned systems and associated countermeasures on the battlefield has been steadily increasing over the last 15 years. Logistic operations may, in turn, benefit from additional unmanned distribution options. Warehouse robots are used by a number of large commercial companies, although this has yet to successfully transition to military warehouses. Work on human augmentation through exoskeletons continues with systems ranging from the 'soft' unpowered OX[1] to the armoured, powered TALOS[2]. Unmanned high-altitude airships that can stay in the air for months at a time offer additional capabilities in surveillance, communications and air-basing.

Materials and manufacturing: Additive manufacturing (AM) is now seeing widespread adoption in the aviation industry and rapidly growing buy-in from other sectors. New developments feature printers that are cheaper, faster, incorporate a greater range of materials and allow embedding of (limited) electronics. Other developments of interest in the military domain include new types of protective, lightweight materials, electromagnetic cloaking materials, self-healing systems and new water generation and treatment technologies.

Sensors: Sensor research facilitates the growing phenomenon of the 'Internet of Things' (IoT), although the manifestation of this trend is more prevalent in civilian than in military organisations. Novel sensors also enable more sophisticated detection devices such as the Black Canary for airborne chemical detection. Research continues to develop sensors for GPS-independent navigation and laser-based spatial awareness.

ICT: Digitisation of enterprises, the IoT and the associated generation of 'big data' is one of the most significant influences shaping social and economic structures in recent times. For military logistics, this means more sophisticated logistic information systems with a greater range of predictive and risk-management capabilities, although often at the expense of system transparency. Sophisticated AI systems have moved closer to becoming a major disruptive influence in both the military and civilian domains. In communications, the availability of small cheap satellites is increasing access to space for communication and surveillance. At the same time, large companies such as Google and Facebook are working on solutions for ubiquitous global connectivity. Mixed and virtual reality systems

[1] Operational Exoskeleton – formerly known as the Flexoskeleton
[2] Tactical Assault Light Operator Suit

have recently entered the consumer market and developers are starting to explore applications in data visualisation, tele-assistance, tele-maintenance, and training.

Health: Health technologies draw together advances from a broad range of fields. Robotic surgery is now commonplace for certain types of procedures, although tele-surgery is not yet widely used. AM is used to create customised bone replacement implants, as well as printing some less complex organs such as ears and skin. Sensors and microelectronics are contributing to more sophisticated prosthetics and health-state monitoring devices. Miniaturised portable diagnostic systems reduce the requirement for large pathology laboratories. New approaches are being investigated in wound management and control of bleeding.

Technologies of interest: In assessing technologies of interest from this and previous horizon scanning reports, it is noted that some are now being adopted by allied military forces. This presents an opportunity to leverage allies' experience in the operational use of technologies such as hybrid generators, portable solar panels, energy-scavenging suits, atmospheric water generators, virtual reality panels and additive manufacturing. Concepts of employment can now be developed for maturing technologies such as AM, unmanned supply systems, portable diagnostics and health-state monitoring.

New technologies recommended for close watch include airships and on-demand manufacturing of pharmaceuticals. Airships offer an additional option for large-scale distribution of materiel, infrastructure, and services without a requirement for air-fields. However, protection requirements, extreme weather conditions and platform cost are likely to hinder their use in contested and degraded environments. Technology for on-demand manufacturing of pharmaceuticals is at the initial prototype testing stages and is not yet practically useful for military operations. A close watch is recommended due to its potential for improving robustness and efficiency of Class 8 supply chains once the range of pharmaceuticals improves.

Potential disruptors: New technologies that are likely to directly impact military operations include swarming, AI, armed unmanned systems, and the coordinated use of cyber-warfare. Technologies that may be transformative within the wider society include advanced battery designs (as enablers), driverless vehicles, AM, quantum computing, genetic manipulation and neural interfaces. These developments have some mutual interdependencies and converging of effects that can disrupt existing economic and social models.

Broad recommendations for assessment of military applications of emerging technologies from this and other studies include:

- Consideration of command and control options in degraded and contested environments
- Development of long-term data management and exploitation plans
- Incorporation of emerging technologies in red-teaming
- Ongoing horizon scanning studies
- Development and assessment of detailed concepts of employment for some maturing technologies that offer significant benefits for the ADF CSS.

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Contents

Glossary

3D	Three-dimensional
ADF	Australian Defence Force
AFIRM	Armed Forces Institute of Regenerative Medicine
AI	Artificial Intelligence
ALPS-MC	Adaptive Logistics Planning System – Marine Corps
AM	Additive Manufacturing
AMAS	Autonomous Mobility Applique System
ARDR	Army Research and Development Requirement
ARES	Aerial Reconfigurable Embedded System
BEAR	Battlefield Extraction Assist Robot
C2	Command and Control
C4ISR	Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance
CAF	Canadian Armed Forces
CASEVAC	Casualty Evacuation
CAST	Convoy Active Safety Technologies
CBM	Condition-Based Maintenance
CBRN	Chemical, Biological, Radiological and Nuclear
CERDEC	Communications Electronics Research Development and Engineering Center
CLBT	Configured Load Building Tool
CLIP	Continuous Liquid Interface Production
CMF	Composite Metal Foam
CQC2T	Centre for Quantum Computer and Communications Technology
CRACUNS	Corrosion Resistant Aerial Covert Unmanned Nautical System
C-RAM	Counter Rocket, Artillery and Mortar
CRISP-R	Clustered regularly interspaced short palindromic repeats
CSS	Combat Service Support
CTC	Siderophore cyclic trichrysobactin material
DARPA	Defence Advanced Research Projects Agency (US)
DC	Direct Current
DLA	Defence Logistics Agency
DMLS	Direct Metal Laser Sintering
DNA	Deoxyribonucleic Acids
DoD	Department of Defense (US)
DST	Defence Science and Technology
EAPS	Enhanced Area Protection and Survivability

EM	Electromagnetic
EPA	Embedded Propellant Analyzer
EVPS	Exportable Vehicle Power System
EWS	Emergency Water Station
FALCom	Field-Aided Laminar Composite
FDA	Food and Drug Administration
FIT	Fleet Insight Toolkit
FPGA	Field Programmable Gate Array
GCSS	Global Combat Support System
GE	General Electric
GFT	Genetic Fuzzy Tree
GPS	Global Positioning System
GXV-T	Ground X-Vehicle Technology
HADR	Humanitarian Assistance and Disaster Relief
HALE-D	High Altitude Long Endurance Demonstrator
HAPS	High Altitude Pseudo-Satellite
HEIT	Hybrid Energy ITV (Internally Transportable Vehicle) Trailer
HES	Horizon Energy Systems
HIFiRE	Hypersonic International Flight Research Experimentation
HP	Hewlett-Packard
HUMS	Health and Usage Monitoring System
HUS	Horizon Unmanned Systems
ICT	Information and Communication Technology
IED	Improvised Explosive Device
INS	Inertial Navigation System
IoT	Internet of Things
IP	Intellectual Property
ISIL	Islamic State in Iraq and the Levant
ISR	Intelligence, Surveillance and Reconnaissance
JIC-P	Joint Infantry Company Prototype
JMIDS	Joint Modular Intermodal Distribution System
JMIP	Joint Modular Intermodal Platform
JPADS	Joint Precision Airdrop System
lb	Pound
LEAP	Leading Edge Aviation Propulsion
LHD	Landing Helicopter Dock
Li	Lithium
LIDAR	Light Detection and Ranging
LIS	Logistic Information System

LMP	Logistics Modernisation Programme
LOCUST	Low Cost Unmanned Aerial Vehicle Swarming Technology
LogFAs	Logistic Functional Area Services
LOGSA	Logistic Support Activity
LRED-FCD	Logistics Research and Engineering Directorate Future Concepts Division
LS3	Legged Squad Support System
LTCOL	Lieutenant Colonel
M2M	Machine-to-machine
MATS	Multi-Agent Tactical Sentry
MEMS	Micro-electromechanical system
MFC	Microbial Fuel Cell
MILIS	Military Logistic Information System
MIT	Massachusetts Institute of Technology
MMIST	Mist Mobility Integrated Systems Technology
MoD	Ministry of Defence (UK)
MOLLE	Modular Lightweight Load-carrying Equipment
MR	Mixed Reality
MRAP	Mine Resistant Ambush Protected
MRI	Magnetic Resonance Imaging
MVP	Mojave Volatiles Prospector
NAMTI	Navy Additive Manufacturing Technology Interchange
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
NBA	National Basketball Association
NCAA	National Collegiate Athletic Association
NEO	Non-combatant Evacuation Operation
NFL	National Football League
NSRDEC	Natick Soldier Research, Development and Engineering Centre (US)
NTT	Nippon Telegraph and Telephone
OER	Oxygen Evolution Reaction
ONR	Office of Naval Research
ORR	Oxygen Reduction Reaction
OX	Operational Exoskeleton
PC	Personal Computer
PCR	Polymerase Chain Reaction
PEEK	Portable Eye Examination Kit
PEMFC	Proton Exchange Membrane Fuel Cells
POE	Point of Entry

PRISS	Printable Solid-State li-ion batteries
QKD	Quantum Key Distribution
R&D	Research and Development
RDECOM	Research Development and Engineering Command (US Army)
REDI	Resonance-Enhanced Desorption Ionization
REF	Rapid Equipping Force
REV	Robotic Evacuation Vehicle
REX	Robotic Extraction Vehicle
RF	Radio Frequency
ROS	Robot Operating System
RRAPDS	Remote Readiness Asset Prognostic/Diagnostic System
R-TAF	Rapid Technology Assessment Framework
S&T	Science and Technology
Sabre	Synergetic Air-Breathing Rocket Engine
SBS	Soldier Borne Sensors
SCFT	Shipboard Cargo Flow Tool
SLAC	Stanford Linear Accelerator Centre
SMART	Smart Tissue Autonomous Robot
SMDC	Space and Missile Defence Command-Tech Centre
SME	Subject Matter Expert
SMP	Shape Memory Polymer
SMSS	Squad Mission Support System
SOFC	Solid Oxide Fuel Cells
STEEP	Social, Technological, Environmental, Economic, Political
STF	Shear Thickening Fluid
SUGV	Small Unmanned Ground Vehicle
Sweeper	Short-range Wide-field-of-view Extremely agile Electronically steered Photonic Emitter
SWORDS	Special Weapons Observation Reconnaissance Detection System
TALOS	Tactical Assault Light Operator Suit
TARDEC	Tank Automotive Research, Development and Engineering Centre (US Army)
TLS	Transport Layer Security
TORVICE	Trusted Operation of Robotic Vehicles in a Contested Environment
TRL	Technology Readiness Level
TV	Television
UAS	Unmanned Aerial Systems
UBC	Universal Battery Charger
UGS	Unmanned Ground System
UK	United Kingdom

US	United States
USB	Universal Serial Bus
USSOCOM	US Special Operations Command
UUV	Unmanned Undersea Vehicle
V2V	Vehicle to Vehicle
VP Biosentry	Vital Point Biological Agent Detection, Sampling and Identification
VR	Virtual Reality
VTOL	Vertical Take-Off and Landing
WINS	Warfighter Integrated Navigation System
WPT	Wireless Power Transfer

1. Introduction

Strategic planning and foresight can benefit from the early detection and assessment of emerging trends in society, technology, and the environment. Following on from previous logistics technology horizon scanning studies [1, 2], this report provides updates on the emerging global trends, technology trends, threats and opportunities for Australian Defence Force (ADF) Combat Service Support (CSS), in line with Army Research and Development Requirements (ARDR) 16/0044 and 16/0054. The scope of the study covers technologies that are directly relevant to CSS, as well as a number of technologies that are likely to impact military operations more broadly.

1.1 Conceptual Approach

The conceptual approach to data analysis in this report is informed in part by the work of Holland-Smith [3-5], who points out that the difference between a threat and an opportunity lies in the ability to identify the emerging trend in time and react to it appropriately, as illustrated in Figure 1.

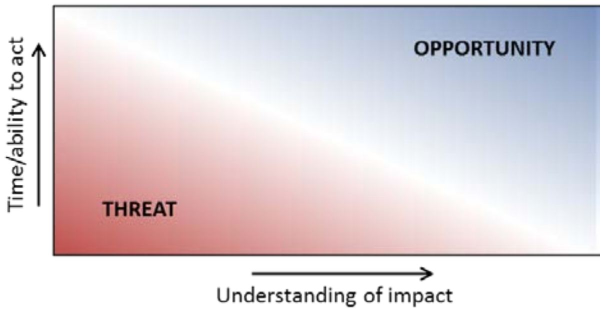


Figure 1 Relationship between emerging trends and threats and opportunities (adapted from [5])

Conversely, disruption arises when we either fail to recognise a threat until it eventuates, or we recognise it too late to do something about it. An example of a largely non-disruptive transformative technology given by Holland-Smith is the roll-out of the Internet. The roll-out took place over a decade, which smoothed out the disruptive effects and yet in that time much of society went from never having heard of the Internet to not being able to function socially without it.

1.2 Report Structure

Figure 2 depicts the structure of the horizon scanning study and the associated approaches and methods. It is broken down into four main parts.

Following the Introduction, Section 2 provides an update on global meta-trends. Section 3 summarises the results of the technology horizon scan for seven technology areas derived from an ADF-tailored taxonomy by Dexter and Krysiak [6]. These include: power and energy, transportation, robotic and autonomous systems, materials and manufacturing,

sensors, ICT, and health technologies[3]. Data collection for the horizon scan is based on ongoing scans of relevant Science and Technology (S&T) publications and technology reports. The information collected is initially assessed for relevance and subjected to thematic analysis. Full details are given in Appendices A through G.

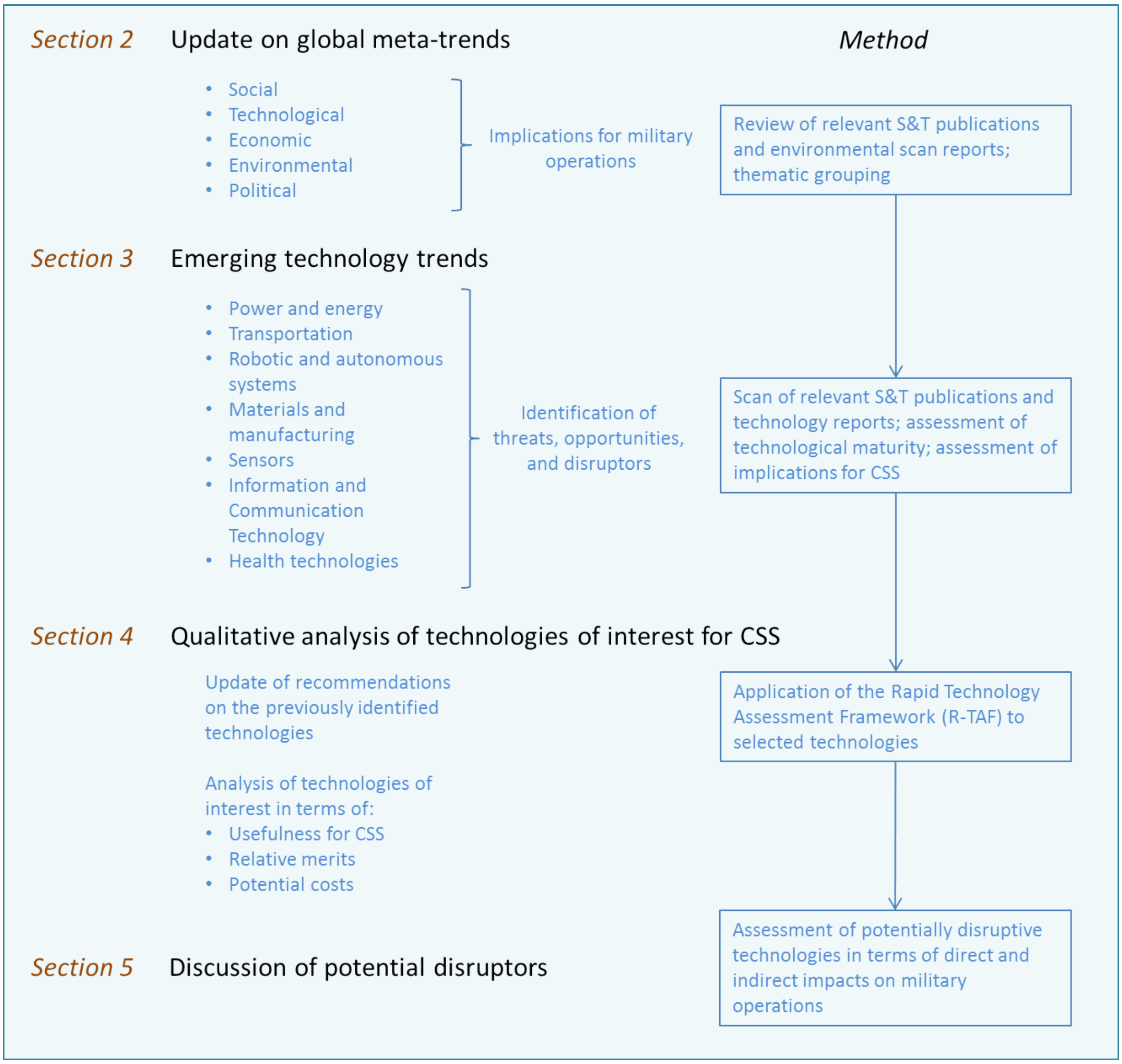


Figure 2 Horizon scanning study structure and method

The qualitative analysis of selected technologies, presented in Section 4, is based on the Rapid Technology Assessment Framework (R-TAF). This CSS-centric framework was developed by the authors for preliminary technology assessments [7]. It has been further refined as outlined in Appendix H by incorporating technology discriminators identified

[3] Unlike the original taxonomy, this report does not include weapons and protection systems as separate groupings.

by Army Headquarters subject-matter experts (SMEs) in recent workshops. At a fundamental level, it considers three key questions:

1. Is the technology useful for CSS?
2. Is it better than the current solution?
3. What are the costs involved?

A discussion of potential disruptors is given in Section 5. This study differentiates potential disruptors into 'direct' disruptors that are likely to require significant changes in military concepts of operations, and 'indirect' disruptors that will influence military operations as a side-effect of transforming the way societies operate and conduct business.

Following a general discussion of horizon scanning studies and disruptive effects in Section 6, the study findings and technology recommendations are summarised in Section 7, which is intended to assist logistics planners in assessing the key drivers for future operational concepts.

2. Update on Global Meta-Trends

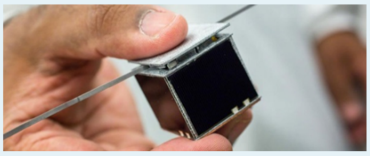
In this report, the prevailing meta trends are broken down by STEEP sectors: Social, Technological, Environmental, Economic and Political [8]. The key trends in these sectors and the impacts on military operations are summarised in Figure 3.

Social

bbc.com

- Disenfranchisement with established government models
- Concerns around privacy and digital security
- Regulatory frameworks lagging behind new business models and technologies
- Concerns about automation of jobs
- Urbanisation and mega-cities
- Ageing and growing population

Technological



sciencealert.com

- Digitisation of private life and state enterprise
- Data as commercial resource
- Accelerating technological change
- Globalisation of technology
- Crowd-sourcing of innovation
- Increased automation of tasks
- Shift to renewable energy
- Access to new resource domains: space, sea-beds, Arctic

Environmental

abc.nect.au

- Climate change
- Melting Arctic caps and glaciers
- Risk of natural disasters, resource shortages, loss of coastal infrastructure
- Risk of mass migration

Economic

vivaenergy.com.au

- Global economic instability and financial austerity
- Reduced R&D spending and military budgets in Western nations
- Globalisation
- Increased dependence on global supply chains
- Deteriorating liquid fuel security in Australia
- Global interest in new resource domains: space, sea-beds, Arctic

Political

abc.net.au

- Rise in economic and technological capability in China
- US Third Offset Strategy
- Regional expansion and economic pressures exerted by superpowers
- Increase in sectarian conflicts in Middle East
- Proliferation and global influence of transnational terrorist organisations

Impact on military operations

- Ready transfer of advanced technologies to state and non-state actors
- Privatisation of security and intelligence services
- Changing nature of threat with weaponised autonomous systems, increased lethality and range of munitions
- Shift in technological edge
- Increasingly dispersed operations
- Concurrency requirements
- Potentially greater requirement for border security, HADR, and stabilisation operations (in urban, littoral and amphibious contexts)
- New contested domains: Arctic, space, sea-beds

Figure 3 Summary of global meta-trends

2.1 Social Trends

Beyond the well-recognised long-term trends of urbanisation and ageing populations [9], the last few years have seen increased social tensions around the perception of social inequality within the established government and economic models in Western nations. This has resulted in the growing popularity of the more polarised right and left political movements, exemplified by the popularity of Donald Trump and Bernie Sanders in the United States (US), Norbet Hofer and Alexander Van der Bellen in Austria, the recent result of the 'Brexit' referendum, as well as the swing towards independents in Australian elections. This has contributed to an overall (relative) increase in social instability and uncertainty.

In addition, the pervasive and rapidly changing technological landscape has given rise to concerns around privacy and digital security [10], pervasive surveillance [10], the potential impact of automation on jobs [11], and the ability of regulatory frameworks to keep up with emerging technologies and business models [12].

2.2 Technological Trends

Digitisation of all aspects of private life and state enterprise continues, with the networking of increasingly greater numbers of devices and objects [13]. Consumer data is increasingly treated as a valuable commercial resource [14] and monitoring of our digital identities is taking place at both the commercial and government levels [10].

At the same time, digitisation of information has been one of the key enablers of global access to sophisticated technology. Schools, universities and individual consumers now routinely buy 3D printers that have become valuable in the rapid prototyping of new designs. The design solutions are, in turn, instantly shared across the world. This crowd-sourcing of innovation is one of the enablers of accelerating technological change.

The acceleration of technological development and cross-pollination of different disciplines are making it increasingly harder to make predictions of the shape of society in the next 30-50 years, introducing additional uncertainty to strategic decision-making. For example, some of the exponential development trends that we can now observe include [15]:

- Doubling of microchip performance every 18 months
- Doubling of data storage capacity every 9 months
- Doubling of the numbers of personal and service robots every 9 months
- Doubling of the number of 'important' discoveries (as determined by the US Patent Office) every 20 years since 1750.

In addition, technological developments are opening access to new physical domains with new projects in the exploration of space, deep sea and the Arctic, especially with the promise of access to previously unreachable resources.

2.3 Environmental Trends

Climate change remains the key global concern [10] with observed melting of the Arctic caps and glaciers in the Himalayas [16] and rising temperature records in the last three years [17]. While precise modelling of climate change effects remains elusive, potential risks include an increase in the number and severity of natural disasters, loss of coastal infrastructure with rising sea levels, resource shortage and mass migration [10, 17, 18].

2.4 Economic Trends

The conditions of economic instability and financial austerity have persisted since the Global Financial Crisis in 2007 and have driven down the research and development (R&D) budgets in most Western nations [19]. The impact of this trend on the geopolitical balance is exacerbated by the reverse trends in other areas of the world, such as China, where the R&D budgets have been growing [10].

The long-term trend of globalisation has significantly increased Australia's dependence on global supply chains for a wide range of products, with concurrent loss of indigenous manufacturing capability. This is particularly noticeable in its effect on Australia's liquid fuel demands, 90% of which are now met by imports [20]. The number of refineries in Australia has reduced to four, down from seven in 2012. In 2014, there was a significant risk of losing the Geelong Shell Refinery as well, which produces military grade fuel used for LHD[4]-based helicopters [20]. The refinery has since been taken over by Viva Energy Australia and continues to operate [21].

Economic uncertainty in the context of globalisation creates an environment of both instability and interdependence, where it is difficult for any one nation to separate itself from events in other parts of the world.

At the same time, the competition for new resources has increased in intensity, with claims for mining rights being pursued by the major players in the Arctic region and in deep-water sea beds. Looking further out, asteroid mining is being investigated for commercial viability by companies such as Deep Space Industries and may open another contested environment in space [22].

2.5 Political Trends

The geopolitical scene is witnessing a gradual rise of economic and technological capability towards China. Analysis by the International Monetary Fund shows that in 2014 China's economy surpassed that of the US when adjusted for spending power[5]. China is also increasing its R&D expenditure and will surpass the US by 2021 if current trends continue [10]. This can be expected to have an effect on the overall technological edge. As examples, in 2012, China dominated in the number of patents granted [10] and the

[4] Landing Helicopter Dock (LHD) platforms underpin Australia's future amphibious capability.
[5] 'Spending power' in this instance refers to the relative buying capacity of a US dollar, which is greater in China than it is in the US. In absolute dollar terms the US is expected to maintain its lead for several more decades.

National Natural Science Foundation of China is now the leading funding agency for autonomous systems [23]. Investments in military technology are also being made in a number of other countries, including Russia.

The counter-trend has been the establishment of the US Third Offset Strategy, which seeks to 'leverage of its core competencies in unmanned systems, long-range and low-observable airpower, undersea warfare and complex systems engineering' [24].

In addition to the technology race, we are seeing regional expansion and economic pressures from global superpowers with the recent annexation of Crimea by Russia and the ongoing conflict in Ukraine [25]. The tensions around China's expansion in the South China Sea have been exacerbated by the recent Hague ruling that refuted China's claims to this territory, including the Paracel and Spratly Islands, which show signs of being militarised by the Chinese government (shown in Figure 4) [26]. The fact that a quarter of global shipping routes go through this area and Australia's dependence on global supply chains make this developing situation particularly relevant for the nation.

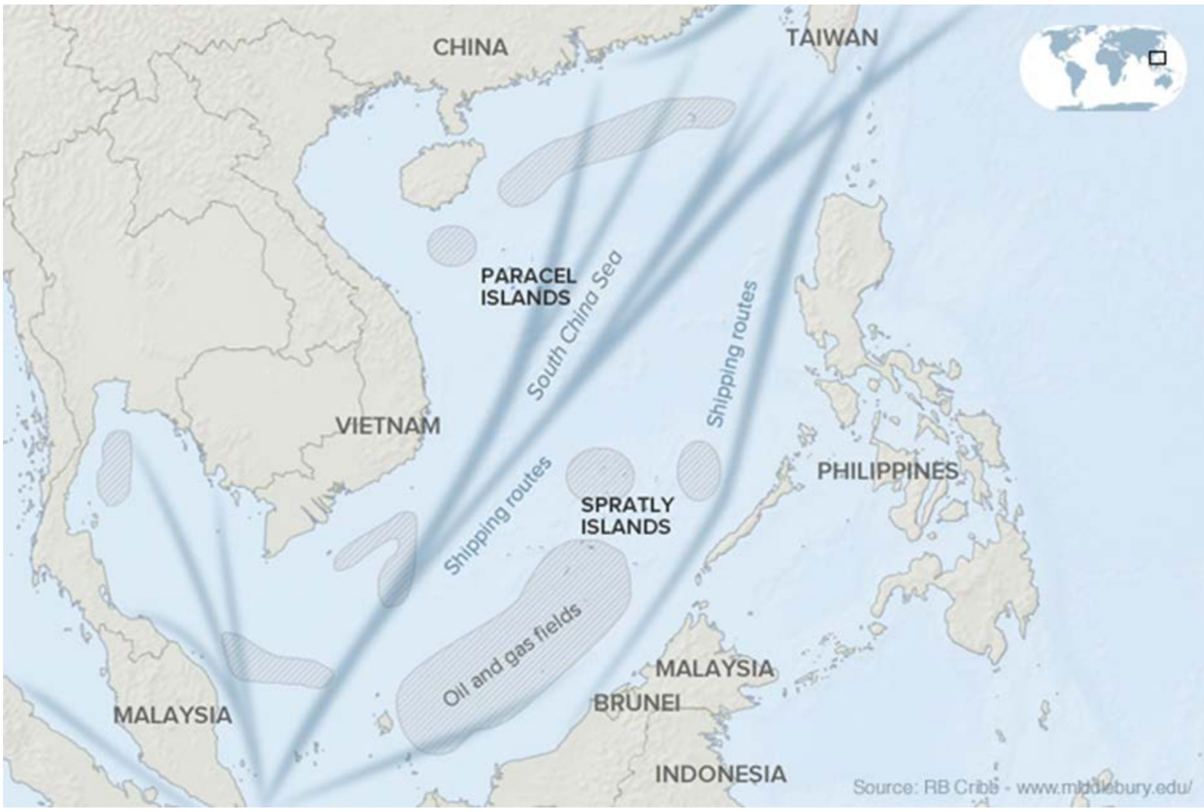


Figure 4 Map of the South China Sea showing disputed territories and shipping routes [26]

Sectarian conflicts in the Middle East continue unabated, giving rise to the recent emergence of ISIL[6] as one of the more prominent transnational terrorist organisations. In a similar way, large criminal syndicates continue to operate outside state bounds, particularly in Central America [9].

[6] Islamic State in Iraq and the Levant

2.6 Implications for Military Operations

These global trends can be expected to have a number of influences on the nature of military operations. Digitisation of information and globalisation of trade means that both state and non-state actors have ready access to advanced technologies. An example of this is low-cost Global Positioning System (GPS) jammers that can be bought online, or readily available cheap drones. The latter are now routinely used in conflicts for surveillance, targeting and as improvised explosive devices (IEDs). Other potential payloads include small arms and converted munitions, chemical and biological weapons and radio-frequency (RF) devices [12, 25]. Figure 5 shows an example of commercial drones used for surveillance in Ukraine.

Figure 5 DJI Phantom 2 drones sent by US support groups to Ukrainian National Guard [12]

Beyond these improvised applications, military weaponised autonomous systems are being developed by all of the major global players. New concepts such as 'loitering munition' are demonstrated by Aerovironment's Switchblade [12]. Israel Aerospace Industries' Harpy and Harop drones are designed to home in on the radio emissions of air-defence systems and destroy them by crashing into them, kamikaze-style. In South Korea, DoDAAM System's sentry robot, Super aEgis II, is equipped with a machine gun and uses computer vision to detect and fire at human targets within a 3 km range. The US Talon SWORDS[7] robot can carry an M16 and other weapons. The Russian Uran-9 is an unmanned vehicle armed with a 30-mm cannon and antitank guided missiles. The Chinese

[7] Special Weapons Observation Reconnaissance Detection System

arsenal of unmanned systems includes the Divine Eagle high-altitude drone used to destroy stealth bombers [27].

An increase in the range and lethality of munitions has contributed to increasingly dispersed operations, both due to extended reach and to enable survivability [9, 15, 25]. Battlelines have given way to dispersed, disaggregated, nodal operations with a poorly defined adversary, and often take place within civilian settlements. This disaggregation of the battlespace is exacerbated by urbanisation. As cities grow, some governments may fail to provide adequate security, employment, infrastructure, and services. This enables urban areas to become safe havens and strongholds for terrorists, insurgents and criminal organisations [9].

If current projections of climate change effects take place, we can expect an increased requirement for border security operations, humanitarian assistance and disaster relief (HADR), and peace-keeping efforts. These are likely to take place in urban and littoral/coastal environments. Melting of the Arctic and Antarctic poles will increase competition for resources in this region. Due to technological developments, new contested domains may also open up in space and in deep-sea mining.

At the same time, increased digitisation of the state enterprise has led to the pervasive trend of well-funded cyber-attacks becoming a standard tool for achieving national interests for most countries, as highlighted recently [28].

Overall, the global trends across the STEEP sectors are pointing towards requirement for agile, concurrent and dispersed operations within populated environments, and in the context of geopolitical and climatic instability.

3. Horizon Scan of Emerging Technologies

The information gathered during continuing scans of relevant S&T publications and technology reports is initially assessed for relevance and subjected to thematic analysis within seven technology areas:

- Power and energy
- Transportation
- Robotic and autonomous systems
- Materials and manufacturing
- Sensors
- Information and Communication Technology (ICT)
- Health technologies.

A summary of the more significant and logistics-relevant technologies is given below for each of the above technology areas. An assessment of the Technology Readiness Level (TRL) of each technology is also provided. The TRL scale comprises nine levels, from level 1 (very low maturity where basic principles are observed and reported), through to level 9 (where system technology has been qualified through successful mission operations). The TRL assessment used in this report is based on military applications of technology, rather than its commercial use. A caveat in using the TRL scale is that there isn't necessarily a linear relationship between TRL and the time or resources required to develop a technology to operational maturity, as technologies develop at different rates. Some consumer electronics can go from TRL 3 to 7 within a couple of years, whereas others (e.g. compact nuclear fusion, supercapacitors), have faced technical challenges for several decades.

3.1 Power and Energy

Developments in power and energy generation, storage and transmission have become a significant area of research as the global shift towards renewable energy continues. These include advances in areas such as battery designs and hybrid systems for better power management, fuel cells and supercapacitors, solar technology including improved photovoltaics, and development of practical energy harvesting and scavenging systems. Some of the more novel approaches include the mimicking of photosynthesis to produce fuels and other chemical products such as acetate, harvesting of power from humidity and electromagnetic (EM) waves, and incorporation of supercapacitors into 'smart' fabrics. Figure 6 shows examples of these technologies and their relative technological maturity on the TRL scale.

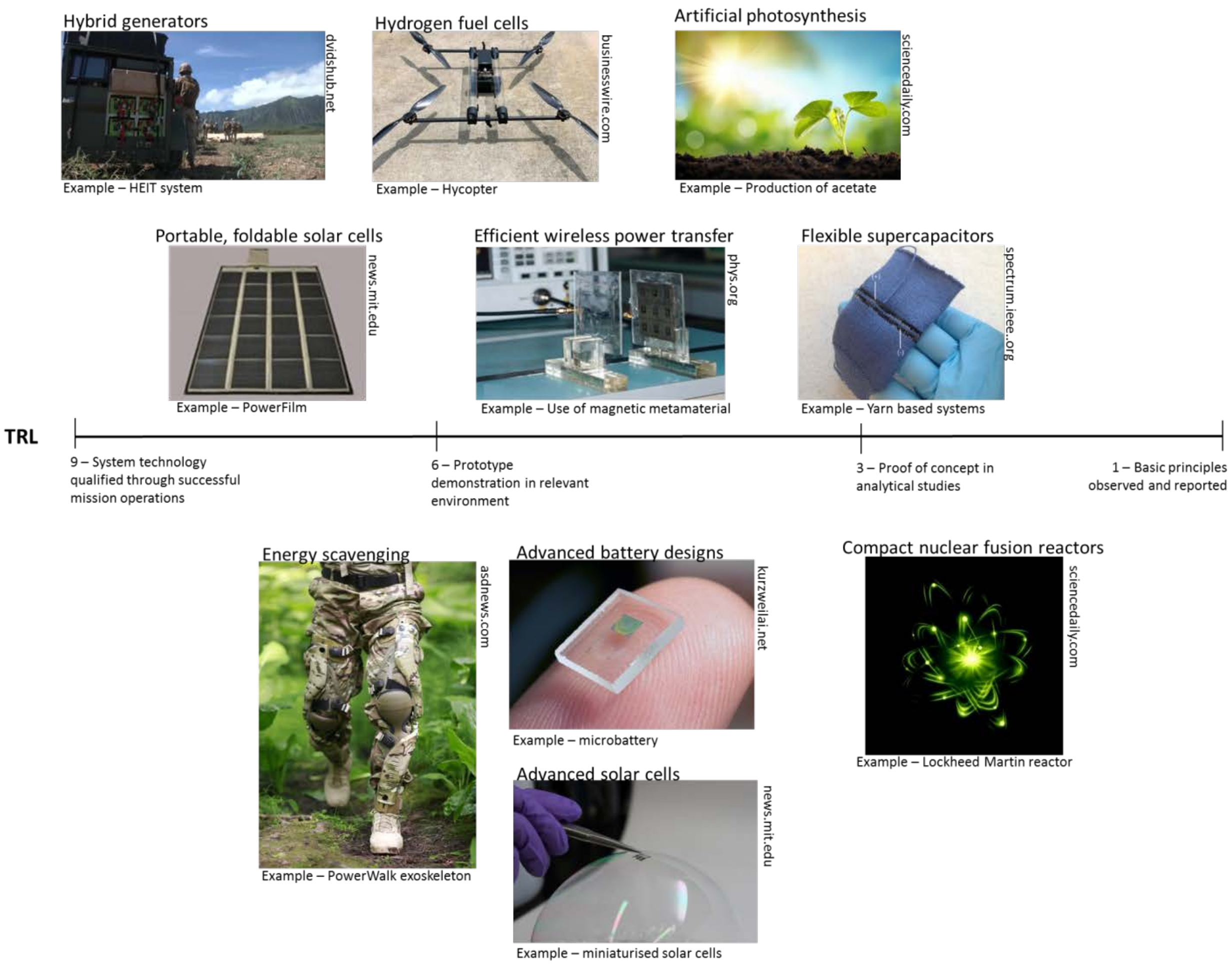


Figure 6 Examples of emerging power and energy systems

3.1.1 Batteries

The global shift to renewable energy, growing popularity of electric cars and proliferation of consumer electronics and small Unmanned Aerial Systems (UAS) models has driven the requirement for new battery designs that are smaller, lighter, safer, cheaper, charge faster and last longer. A number of research projects are ongoing in improving the performance and safety of lithium-ion (li-ion) batteries [29-33]. For example, researchers in South Korea have developed Printable Solid-State (PRISS) li-ion batteries that consist of paste and slurry-like materials and can be printed onto a surface of the required shape [31]. New structural designs include use of semi-solid colloidal suspension electrodes, which give flexible, resilient batteries [34], semi-liquid batteries [32], flat-pack assembly structures [35] and nanowire based assemblies [36].

Miniaturisation of batteries is a viable direction with the advent of sensor-based monitoring across a range of industries. Micro-batteries that can be integrated into microchips during production have been developed with use of lithography techniques for potential applications in miniaturised (and embedded) sensors [37]. At the University

of Illinois, researchers have demonstrated miniaturised batteries combined with solar cells that give a flexible, wearable mesh for use in health-state monitoring devices and other applications where flexibility is important [38].

Some novel approaches to battery design include a paper-based biologically-powered battery that creates power from microbial respiration [39] and solid state batteries that promise longer life and improved safety [40]. Advances in redox-flow batteries have been shown with use of safer materials [41, 42]. Batteries utilising alternative chemistries and materials are being developed, including aluminium batteries [43], sodium-ion [44] and magnesium-ion [45] batteries, metal-air batteries including zinc-air [46] and lithium-air [47, 48], a sodium-magnesium hybrid [49], and advances in alternative electrode materials such as silicon [50-52]. These alternatives can potentially deliver the advantages of longer life, ultrafast charging and safer design, but require further development to become commercially viable and competitive with the near-ubiquitous li-ion battery.

Overall, the more unconventional or novel battery designs that promise significant leaps in performance are currently at the low to mid-TRL level of development (TRL 3-5). In most cases, there are technical challenges that need to be overcome to demonstrate significant advantages over existing li-ion batteries and to commercialise the systems. However, as battery designs improve, they can be expected to give a significant boost to other industries, such as the renewable energy market, all-electric vehicles, the Internet of Things, and the use of small-to-medium size UAS. This can have disruptive effects on existing industries, as we are now seeing with home energy storage technologies such as the Tesla Powerwall battery [53] and the more readily scalable Redflow ZCell [54], which is starting to impact traditional grid-based electricity suppliers.

3.1.2 Supercapacitors

Supercapacitors remain a key subject of interest because of their known and realisable advantages over batteries: superior power density (faster charge times and higher power delivery) and minimal charge cycle degradation (longer life). However, batteries retain the advantage of significantly higher energy density. Hence, as in our previous reports [1, 2] the promise of commercially viable supercapacitors that deliver superfast charging speeds with energy density comparable to batteries is yet to be realised. Improving energy density and their application to wearable electronics are the two dominant drivers behind current supercapacitor research, with a third being the exploration of alternative, less exotic and hence less expensive materials and manufacturing processes, to open the way for commercial-scale production.

Ongoing improvements in capacitor and supercapacitor design include the use of nanomaterial electrodes [55], 3D printed graphene electrodes [56], graphene electrodes manufactured in a low-temperature process for superior electrochemical characteristics [57], and asymmetric supercapacitors that use different materials for each electrode [58]. A number of research projects are looking at yarn-based designs for flexible supercapacitors based on embedded activated carbon particles [59], magnetic-assisted self-healing yarns [60], and niobium nanowires [61]. Flexible systems can be integrated into 'smart' fabrics that allow a range of monitoring and interactive functions and have potential applications

in soldier uniforms (See Section 3.4 – Materials and Manufacturing). Paper-based supercapacitors have also been developed, setting records for the highest charge and capacitance in organic electronics [62], and rivalling that of traditional supercapacitors. Micro-supercapacitors have also been developed to serve as energy storage devices embedded directly into microelectronics [63, 64], mirroring the equivalent development in micro-battery technology. However, none of the reported designs have yet progressed to functional and complete prototype testing.

3.1.3 Fuel Cells

Solid Oxide Fuel Cells (SOFC) are a type of fuel cell that generally use a hard, non-porous ceramic compound as an electrolyte through which oxygen ions move, and operate at high temperatures (600-1000 degrees C) [65]. Large-scale units are already used in lieu of generators to power building sites, data centres and other infrastructure by companies such as Google, Apple, eBay and Microsoft [66, 67]. Their popularity is due to better efficiency compared to traditional internal combustion engine-based generators. Continuing advances in this type of fuel cell technology include improvements in electrolyte materials [68, 69] and miniaturisation for use in small electronic devices [70], bucking the trend for SOFC to be used in large-scale applications.

Proton Exchange Membrane Fuel Cells (PEMFC) are another type of fuel cell that use a thin membrane through which protons move. A new non-platinum catalyst for use in PEMFC has been developed by researchers in China, with the promise of reduced manufacturing costs [71], complementing recent developments in new (cheaper and more effective) membrane materials [72].

There has also been renewed interest in fuel cells powered by hydrogen, with two companies now demonstrating their use within small UAS: Horizon Unmanned Systems' (HUS) HYCOPTER [73] and Intelligent Systems' DJI Matrice 100 [74]. While weighing less than the batteries they replace, hydrogen fuel cells allow significant improvements in UAS range and endurance. The risks associated with hydrogen fuel (flammability, easy ignition, hard to detect leaks) are still flagged as potential concerns, as is finding a method for generating hydrogen fuel that is both sustainable and cost-effective. Current large-scale production methods rely on breaking down natural gas and other hydrocarbons although progress is being made on making sustainable techniques cost effective (see Section 3.1.6).

Another example of miniaturisation of fuel cells is the microbial fuel cell (MFC) developed at Bristol Robotics Laboratory in the United Kingdom (UK). The system essentially generates power for a small robot by processing dirty water, which is a step towards energy autonomy for electronic systems although a lot of optimisation is still required [75].

3.1.4 Energy Harvesting and Scavenging

Energy harvesting and scavenging technologies cover a range of approaches and energy sources, including well-known sources such as movement, heat (through

thermoelectricity), pressure (through piezoelectricity) and triboelectricity[8]. Some newer sources have also risen in prominence, including EM radiation, sound energy, and changes in humidity. The differentiation between harvesting and scavenging is in some sense artificial. Scavenging tends to refer to taking advantage of waste energy sources from other energy-generating processes (e.g. heat from the exhaust gases of an internal combustion engine), whereas harvesting can be from any source, even though the mechanisms for collection may be identical.

Much of the extant energy harvesting/scavenging technology is in the low to mid-TRL range, although several systems are nearing production. An example of one that is being implemented in the military environment is the Kinetic Energy Harvester developed by PowerWalk [76]. This light-weight, leg-mounted exoskeleton is designed to allow a full range of (supported) motion and harvests energy from walking. Field tests with US Marine Corps and the US Army are scheduled for 2017. Another is an Energy Harvesting Backpack [77] being developed by the US Army Research Laboratory. A related, high-TRL technology based on converting mechanical energy directly into electricity is a shoe insert utilising a novel conversion technology called reverse electrowetting [78], and is currently being commercialised.

At the lower end of the TRL scale are devices exploiting changes in humidity [79, 80], and a nanopaper-based piezoelectric generator that generates electricity from touch [81]. In addition, researchers are investigating the potential for harvesting energy from sound through the triboelectric effect [82]. Advances in thermoelectricity include improvements to the composition [83, 84] and nanostructuring [85] of thermoelectric materials, and two new approaches that include the use of quantum dots [86] and rectennas[9] [87].

Ohio State University researchers are fielding technology for capturing some of the wasted EM radiation from mobile phones that can be built into mobile phone cases [88]. Taking this a step further, Drayson Technologies have recently unveiled their commercially available new technology 'Freevolt' for harvesting ambient RF energy [89]. This type of device may help extend the battery life of portable electronics, although only small amounts of energy (in relative terms) can be harvested this way and the energy generated will fluctuate.

3.1.5 Solar Photovoltaic Cells

Improvements in traditional solar photovoltaics are ongoing for a variety of applications, including military systems. For example, the PowerFilm foldable, lightweight panel has been awarded a manufacturing contract for use in tandem with the Universal Battery Charger (UBC) [90]. Improvements in existing technology include miniaturisation [91], and various designs and coatings for capturing more incident light [92] and more of the electromagnetic spectrum [93, 94]. Exotic multi-junction solar cells also capture more of the

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[8] The triboelectric effect is similar to static electricity generated when materials with different electric potential are rubbed together, or brought together and separated.

[9] Rectennas combine the functions of an antenna and a rectifier. It is a type of antenna that can convert electromagnetic energy into direct current (DC) electricity.

electromagnetic spectrum [95], but are substantially more expensive to produce than traditional silicon solar cells.

Perovskite cells[10] have been of interest for some time, mainly due to their low cost and ease of production. There have been significant efficiency gains over time, although the challenges of stability and commercial reproducibility still remain. Some recent research has focused on improving efficiency through changes in the crystal fabrication process [96] and using more efficient manufacturing techniques and cheaper materials that both improve conversion efficiency and capture a broader spectrum of light [97, 98]. Other developments include improving stability through simplifying their structure [99], and investigating perovskite combined with graphene replacing tin oxide electrodes [100] and with silicon photovoltaic cells [101].

Polymer solar cells, including organic solar cells, also present a potentially cheaper alternative to traditional silicon-based cells, but have traditionally had very low conversion efficiency. Nonetheless, such small, extremely cheap solar cells are seen as a potential solution to powering the potentially trillions of sensors embedded within the Internet-of-Things [102]. Some new manufacturing approaches with use of microscopic rakes [103] have helped double the energy output, but it is still significantly lower than silicon cells. Research into the materials used [104] and the light conversion process in such solar cells [105] is ongoing.

Other new developments include the production of 'kesterite' solar cells in Germany using a 3D printing technique, with a relatively low conversion efficiency but significant advantages in terms of industrial production [106]. Another technology on the lower end of the TRL scale is a solar cell comprising curled nanowires [107], and one comprising optical rectennas [108]. Although not strictly photovoltaics, a new approach to storing solar energy directly as chemical energy is being developed that uses shape-changing molecules, although the process of controlling the shape reversion (release of energy) needs refinement [109].

Overall, the development trends point towards more efficient, smaller and more flexible solar cells that (combined with new energy storage and management solutions) present new options for power generation on deployments.

3.1.6 Artificial Photosynthesis and Fuel Synthesis

Artificial photosynthesis refers to technology that mimics the natural photosynthetic process to use energy in sunlight for conversion of carbon dioxide and water into hydrocarbons and other products. One highlight includes a recent advance by researchers at Caltech, who have demonstrated a new process for creating hydrogen fuel by splitting water molecules that improves on existing photosynthetic techniques by factors of 5 to 10 [110]. Another highlight is the development of a system based on nanowires and bacteria to synthesize acetate [111], the most common building block for biosynthesis. It can form

[10] Perovskite solar cells use perovskite structured compounds, usually hybrid organic-inorganic lead or tin halide-based materials. A perovskite material has the ABX_3 chemical formula and a cubic-symmetry structure.

the basis for other valuable chemical products, including biodegradable plastics, pharmaceuticals and liquid fuels. In similar research, an engineered enzyme within a microbial pathway has been used to produce biosynthetic (i.e. renewable) propane [112]. There have also been general improvements in the efficiency and cost of catalyst materials for photosynthesis, synthesis and electrolysis to produce fuels, e.g. [113-116].

In general these technologies are largely at the proof-of-concept demonstration stage, with no commercial systems as yet. The long-term potential for military operations is in-situ generation of fuel and other compounds.

3.1.7 Compact Nuclear Fusion

Research to develop compact nuclear fusion reactors continues despite the scepticism both within parts of the scientific community and society more generally about the feasibility and cost-effectiveness of this technology. Lockheed Martin has claimed a breakthrough in containment technology [10], although it is yet to be demonstrated or detailed in scientific publications. MIT[11] researchers are investigating new, compact reactor designs based on advances in superconductors to produce high magnetic field coils for improved efficiency [117]. In Sweden and Iceland, researchers claim feasibility of an alternative nuclear fusion reaction, utilising far smaller and simpler reactors for both heat and electricity, and that produces almost no neutrons, thus making it safer overall [118]. However, all these projects are yet to successfully complete the proof-of-concept stage.

3.1.8 Wireless Power Transfer

Wireless charging technology is already in use for (smaller) consumer electronic devices, such as smartphones and watches, despite shortfalls in terms of efficiency, charging distance and directionality. This type of wireless power transfer is known as non-radiative wireless power transfer (WPT) and is typified in the consumer electronics world by extremely short distances (less than 5 mm), low power transfer, and being highly directional. Some improvements in efficiency were achieved by Chinese researchers (to 20% over 4 cm, up from a only few percent) who embedded magnetic metamaterials into the coils used in WPT [119]. Russian researchers have upped this to 80% over 20 cm through replacing copper coils with ceramic resonators, with improved omnidirectionality [120]. A more omnidirectional approach was developed by researchers in South Korea with WPT technology that allows charging of mobile devices in any location and direction within a designated area [121], although this is less efficient than conventional WPT. Applications for WPT exist in portable and wearable electronics, implanted devices, and electric vehicles.

3.2 Transportation

The big story in transportation has been automation of various driver functions and progress towards driverless vehicles (which in the military context may also be entirely unmanned). This section also touches on developments in associated technologies such as

[11] Massachusetts Institute of Technology

containers and airless tyre designs, and alternative transportation approaches such as precision air-drop and evolution of long-distance hypersonic flight. A further interesting development for logistics is in the advancement of the airship concept. Some examples of these technologies and their TRL can be seen in Figure 7.

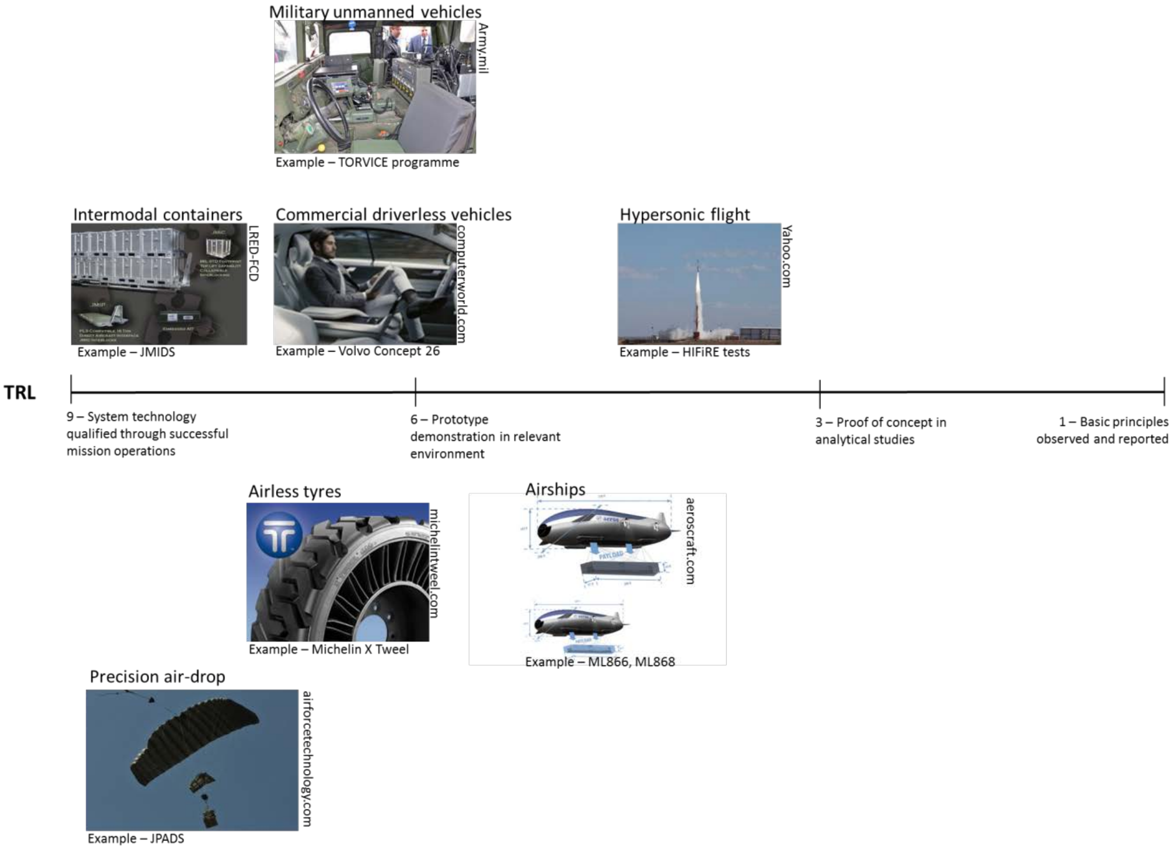

Figure 7 Examples of emerging transportation technology

3.2.1 Autonomous and Semi-Autonomous Vehicle Technology

The global trend towards adoption of driverless vehicles is growing, with most major car manufacturers now funding research projects into this technology. Driverless vehicles are expected to provide the benefits of improved driver safety, better fuel efficiency, reduced congestion and pollution, and broader mobility options for the elderly and disabled [122]. A lot of policy and regulatory questions are yet to be addressed, including a liability regime and EM spectrum allocation for short-distance vehicle-to-vehicle communication. Technical challenges remain in improving the accuracy of navigation (currently a mixture of GPS and Inertial Navigation Systems (INS)), information security and accepted failure rates. Public acceptance is likely to be tested with the first (minor) accident with a Google car [123] and the first death of a Tesla driver whose car was in autonomous mode [124]. In the latter case, the car's sensors failed to distinguish between a large white 18-wheel truck crossing the road and the white of the sky, causing a collision and death of the Tesla driver, Joshua Brown of Ohio, USA. While the overall safety records of both vehicles

remain impressive when compared to conventionally-piloted vehicles, both stories made headlines around the globe, indicating a close interest and low tolerance of failure for this technology. Volvo became the first car-maker to address the issue of liability by stating that the manufacturers should take responsibility for the actions of the car whilst in full autonomous mode [125].

Numerous models of autonomous vehicle are now undergoing testing for civilian markets. Google announced its Citymobil prototype in 2014 [122]. Volvo's 'Concept 26' sedan is expected to be released commercially in Sweden in 2017 [125]. Toyota is working on 'assistive autonomy' technologies that would take over in dangerous situations [126, 127]. Freightliner and Mercedes (both Daimler subsidiaries) have unveiled driverless truck models, although pricing and timeframe to commercial availability are yet to be confirmed [128]. At least six different companies including Google and General Motors are working towards putting fully autonomous taxis on the market [129, 130]. Robotnik have developed a self-driving car for research and cargo delivery in restricted environments [131] with an open architecture operating system based on the Robot Operating System (ROS) [132].

Military programmes looking at automation of individual vehicles and convoys include the US Army Tank Automotive Research, Development and Engineering Centre's (TARDEC's) Convoy Active Safety Technologies (CAST) and subsequent Autonomous Mobility Applique System (AMAS) [2], which was demonstrated in 2014 [133, 134]. DST Group is also working in collaboration with TARDEC to test autonomy applique kits for military vehicles [135]. The Oshkosh TerraMax conversion kit for retrofitting a range of tactical wheeled vehicles has been demonstrated for the US Marine Corps [136, 137]. These kits include an obstacle avoidance capability and operation in GPS-denied environments. A noteworthy trend is reflected in the Defence Advanced Research Projects Agency's (DARPA) new Ground X-Vehicle Technology (GXV-T) programme that aims to break the 'more armour' paradigm and make future military vehicles smaller, lighter, more agile, mobile and aware. A significant part of this programme is crew augmentation through technologies such as semi-autonomous driving and automation of key crew tasks [138].

For military operations, autonomous and semi-autonomous vehicles have the advantage of potentially extending operational reach into contested spaces while improving soldier safety. For logistic convoys, unmanned vehicles could be robotic follower elements behind manned vehicles, or be used for security escort functions in front of the convoy. However, it must be recognised that there are significant operational differences between military and civilian contexts such as, among others, the highly variable and unstructured environments that are lacking in positional cues [122]. Consequently, developments in civilian technology are unlikely to transition smoothly into a military context.

3.2.2 Aerial Transportation

Precision drop technology is not a new concept, with the US Joint Precision Airdrop System (JPADS) already in operation in the Middle East. The main classes of supply that were air-dropped by the US Department of Defense (DoD) in Afghanistan in 2014 were food, water, and fuel, thus reducing the number of re-supply convoys. The systems range

from microlight (10-150lb payload) to medium (15,000 – 42,000lb payload). They use an airborne guidance unit, electromechanical steering actuators, and a steerable canopy to guide the payloads. Further work continues in improving the accuracy of the drop so as to enable deliveries inside base perimeters [139].

Besides UAS (which are discussed in more detail in Section 3.3.1), new developments in air transport include successful tests of hypersonic rockets in Australia under DST Group's Hypersonic International Flight Research Experimentation (HIFiRE) programme [140]. In the UK, Reaction Engines have also developed the hypersonic Synergetic Air-Breathing Rocket Engine (Sabre) for use in the Skylon single-stage-to-orbit spaceplane [141]. These developments indicate potential increases in range and speed of future weapons and bring us a step closer to practical space travel.

The previously reported Martin Jetpack [142] is now available for sale in New Zealand, with a 120 kg payload capacity [143]. It is targeted at the first responder community, but technical characteristics still limit its applicability in military environments.

A new approach to bulk transportation is reflected in Aeroscraft's large-scale airships with the ML866 model already in operation (66 ton payload) and models ML868 and ML86X in development (250 and 500 ton payloads, respectively). (Hybrid Air Vehicles [144] has similar offerings.) The payload capacity in weight and volume is substantially higher than currently used military planes such as the C-130 and C-17. Furthermore, the new models are expected to be able to land on multiple terrains, including water, gravel, sand and swamp with a landing space requirement of 360 m in diameter [145]. This type of capability can have profound effects on achieving deployment and sustainment of forces. A more in-depth R-TAF based analysis of this technology is provided in Section 4.2.1.

3.2.3 Tyre Designs

Airless tyre designs are already used in civilian applications in lawnmowers, bicycles, loaders, forklifts and other construction, farm and lawn equipment. These include Michelin's X Tweel [146], McLaren's semi-pneumatic solid cushion tyres [147] and Google's Shweel [148]. The Big Tyre company in Australia is now testing the third prototype of its Mining Wheel, which has significant reserve strength and is impact resistant [149]. A more radical design has been developed by SciTech Industries with glass fibre-reinforced PET springs used to generate structural strength and form without inflation [150].

There is some interest in transferring these tyre designs to military use due to durability, reduced requirement for spares, and ability to function even when damaged. However, some uncertainties remain regarding their performance at high speeds and ability to handle uneven terrain, vibrations and debris.

3.2.4 Containers

The US Army Research Development and Engineering Command (RDECOM) have developed the Joint Modular Intermodal Distribution System (JMIDS), which comprises

standardised multimodal modular containers that lock to intermodal platforms [151]. The associated Joint Modular Intermodal Platform (JMIP) is Air Force flight certified and has direct aircraft interface interlocks for the containers. It is expected to facilitate rapid, efficient materiel distribution across air, land and sea without reconfiguration, thus also saving time and reducing troop exposure to IED hazards. Currently, the US DoD is looking to contract for JMIDS to be purchased for all services.

3.3 Automated and Autonomous Systems

Autonomous system designs continue to advance with new, more diverse sensors, advances in computing systems and ground robotics, GPS and alternative navigation techniques, more energy dense power sources, Artificial Intelligence (AI) and biomimetics [152]. These advances mean more diverse payloads, better range and more effective navigation through complex terrain. In the longer term, it is expected that autonomous systems will be teamed up with humans, giving a mix of new capabilities. This, in turn, will require re-examination of operational concepts.

At the same time, increasing volumes of data and the growing complexity of available information will require more autonomy in command and control (C2) decision support for filtering, aggregating and exploitation of data in lower level decisions. Solutions for data transmission, sharing and security are now needed for the introduction of any networked system [152]. The additional challenge is that in terms of handling complexity, machine intelligence is 'brittle'. Similarly, autonomous systems more generally can outperform humans within narrow constraints, but when outside the programmed parameters, they tend to fail[12] [122]. As a result, it is expected that in the military space, the best systems will combine both human and machine intelligence to leverage the advantages of both [153].

Some examples of automated and autonomous systems in different domains are shown in Figure 8.

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[12] A good illustration of potential implications of this effect is in the event that took place on 26 September 1983. On this day, in the midst of the rising tensions of the Cold War, the Soviet automated missile alert system reported the launch of five US intercontinental ballistic missiles aimed at the Soviet Union. Procedures required that this attack be immediately reported to the higher headquarters. However, the officer on duty, LTCOL Stanislav Petrov, judged that a US first strike of only five missiles didn't make sense and was likely to be an error in the new computer system. This judgement was later confirmed: the satellites were picking up false positives from sunlight reflecting off the clouds. In contrast, an automated reporting system would have simply relayed the information as it was programmed to do – potentially triggering a nuclear war.

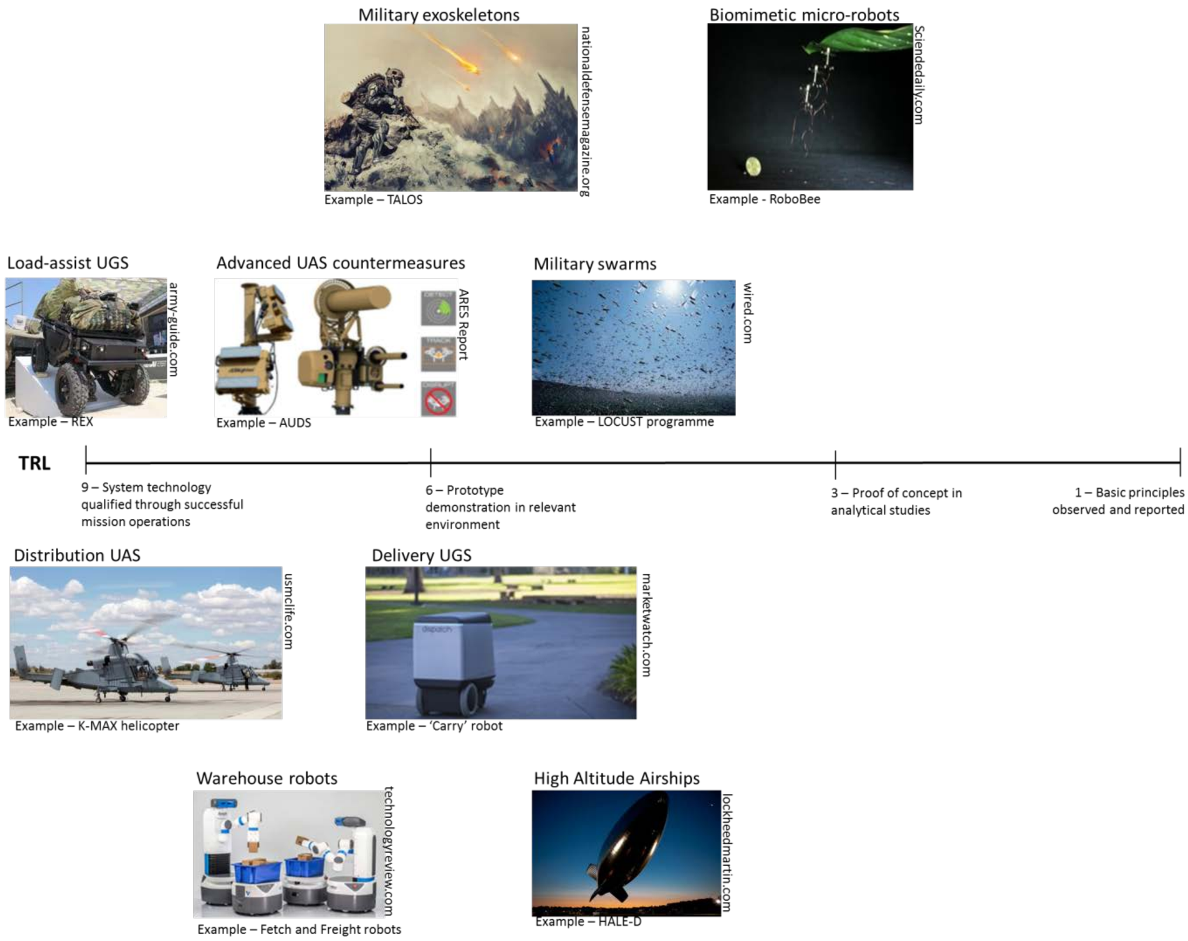

Figure 8 Examples of emerging automated autonomous systems

3.3.1 Unmanned Aerial Systems

The advent of UAS in both the civilian space and on the battlefield is now a widely recognised trend, reflected in the development of a large number of laser-based, cyber, and mechanical anti-UAS systems (e.g. [12, 154-162]). In military settings, UAS are predominantly used for tactical and persistent Intelligence, Surveillance and Reconnaissance (ISR) tasks [122, 163]. There are, however, a number of emerging logistic applications, particularly in distribution tasks. UAS can be broadly classified according to their size and system type.

Smaller, drone-type UAS are generating a lot of interest in the commercial sector for 'last-mile' deliveries, with companies such as Google, Amazon and Walmart already testing systems in relevant environments [10, 164-166]. Drone mail delivery trials have already begun in Switzerland [165] and in Singapore [167]. A Dutch engineering student has developed a defibrillator delivery drone that weights under five pounds and has a range of five square miles [10]. On the very small end of scale, biological organisms are inspiring micro-UAS designs such as Harvard University's RoboBee [168, 169] However,

clarification of regulatory frameworks, robustness of long-range communications and navigation in complex environments still remain as key challenges in the successful implementation of this concept. The technical barriers revolve around payload capacity and range of the smaller systems. Within military environments, small UAS may be developed for delivery of critical (e.g. medical) supplies and equipment for establishing communication links without risking soldier lives.

Medium-sized UAS are predominantly fixed wing systems. They still have limited payload capacity but have significantly higher endurance: a range up to 100 km or several hours of operation[13]. Many are rail-launched, whereas some are launched from an air-frame with self-guiding systems. Examples include Boeing's ScanEagle, Advanced Ceramics Research's SilverFox, AAI's Shadow and the CQ-10A Snowgoose from Mist Mobility Integrated Systems Technology Inc. [170]. While these systems are mostly used for ISR, the US Quick-Meds program has demonstrated a Shadow UAS dropping 9 kg of medical supplies to forward areas [170], and systems such as Snowgoose are well suited for discrete delivery of small quantities of logistic supplies and are less expensive than most other unmanned cargo transportation systems under development [171].

On the larger scale, systems such as Northrop Grumman's MQ-8 Fire Scout and Boeing's A160 Hummingbird are providing persistent ISR capabilities [122]. Kaman K-MAX helicopters have proven themselves in three years of cargo delivery operations in Afghanistan. The US Marine Corps have tested upgraded K-MAX helicopters with 6,000 pound payload capacity for cargo delivery [172] and after initially signalling an indefinite extension to its employment [173] has more recently decided not pursue the capability further [174]. More futuristic designs such as the Aerial Reconfigurable Embedded System (ARES) vertical take-off and landing (VTOL) aircraft are still in development [139].

An interesting new concept under development is the high-altitude airship, such as the High Altitude Long Endurance Demonstrator (HALE-D) built by Lockheed Martin [175]. These are untethered, unmanned, lighter-than-air vehicles designed to operate above the jet stream in geostationary positions and deliver persistent services such as communications relay, ISR, refuelling, or airbases for other UAS [15].

Hybrid designs that allow operation across different domains can be found in systems such as John Hopkins University's Corrosion Resistant Aerial Covert Unmanned Nautical System (CRACUNS). This UAS can stay under water for months without corrosion. When activated by a signal, the CRACUNS rises to the surface and begins its flight [176]. The opposite concept has been developed by the US Naval Research Laboratory with prototypes that can fly then swim [177, 178]. Small experimental systems that combine ground and air capability have been developed at the University of California with an unmanned ground system (UGS) carrying a UAS [179]. A demonstration of the reverse concept on a large scale has been completed with a UGS carried by a K-MAX helicopter in an autonomous re-supply task [180].

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[13] Noting the advances in fuel cells able to extend the endurance of small UAS narrowing this gap.

UAS swarming technology is being developed for military applications at the Pentagon, DARPA and the US Office of Naval Research (ONR), which recently demonstrated its LOCUST (Low Cost Unmanned Aerial Vehicle Swarming Technology) programme [181-185]. Enabling technologies for simultaneous control of multiple UAS are the subject of a number of military and civilian research programmes [186-188]. From a military logistics perspective, this trend should be viewed as a source of potential threat if similar concepts are employed by the adversary.

3.3.2 Unmanned Ground Systems

Unlike aerial systems, smaller ground-based robots entered military operations predominantly for bomb and IED disposal tasks. Today, systems such as iRobot's 110 FirstLook and Small Unmanned Ground Vehicle (SUGV) are also used by US forces for clearance, ISR and CBRN (Chemical, Biological, Radiological and Nuclear) missions [189, 190]. In applications more relevant to logistic tasks specifically, US National Aeronautics and Space Administration (NASA) researchers are developing the Mojave Volatiles Prospector UGS. It is designed to search for water ice and other volatiles that may be underground on various planetary bodies [191, 192]. While still in early stages of development, in-situ resource scavenging has the potential to substantially reduce logistic burden in the long-term. Complementing this, an innovative solution to traversing uncertain terrain has been developed by Harvard University. They have two robot designs: one that uses expandable self-hardening foam and another that drags and piles up sandbags. Both have adaptable algorithms that allow them to work within less predictable environments [193].

Robotic mules that could assist soldiers with loads gained a lot of publicity four to five years ago with flagship projects such as DARPA's Legged Squad Support System (LS3) better known as the 'Big Dog' [194-198] from Boston Dynamics. However, the projected benefits of assisted load-carrying, evacuation and auxiliary power supply have not materialised, as the systems require further R&D investment to make them more robust, mobile, enduring and quieter. Further advances would be needed in controls, AI, human-machine interface, computer vision and robustness. Since then, interest in military applications of such legged squad support systems has waned, and many such programs (including LS3) have been divested by the parent companies. The wheeled versions of squad-support type UGS have fared better with fielding of the REX logistic carrier [199] and Lockheed Martin's Squad Mission Support System (SMSS) [200], which can use waypoint navigation or follow a dismounted soldier. In the civilian space, companies such as Dispatch are investigating UGS options for last-mile delivery of small items [201].

Warehouse robots are already in use with companies such as Kiva (Amazon subsidiary) [202] that developed robots that move shelves around. MIT and Leibniz University of Hannover have both developed autonomous forklifts [203] and Vecna are working on an autonomous pallet handler [204, 205]. Clearpath Robotics have demonstrated OTTO – an autonomous material transporter that can move up to 1500 kg of load [206]. Both Fetch Robotics and the German firm Magazino have improved on Kiva's designs with robots that can pick up items off the shelf, thus removing the need for re-designing an entire warehouse [207, 208]. However, while these robotic systems offer clear efficiency and

accuracy advantages in static and structured civilian warehouses, their value proposition in more dynamic military settings is less clear.

3.3.3 Exoskeletons

Exoskeleton systems are becoming more widespread in medical settings (to assist with rehabilitation and walking for paralysed patients) and in industry for material handling tasks. Examples include Panasonic's ActiveLink, and solutions from Cyberdyne systems and ReWalk, the latter of which has recently been launched in US and Australia to assist paraplegics [209]. Examples of 'soft' exoskeletons are the 'motorised pants' developed at Harvard University, which have sensors to monitor the wearer's motion [210] and the Operational Exoskeleton – OX (previously branded as the Flexoskeleton) developed at DST Group [211, 212]. On the opposite end of the spectrum, the US Special Operations Command (USSOCOM) continues its work on TALOS (Tactical Assault Light Operator Suit), which made headlines in 2013 under the nickname 'Iron Man Suit'. While it does not fly, the current prototypes have in-built cooling, low-light and thermal imaging sensors, power-assisted limbs and ballistic protection armour. General Atomics is also working on a hybrid power supply that will allow the suit to go into a stealth battery mode when required. The suit is expected to be completed for use in special operations in 2018 [213, 214].

Exoskeletons can be used to assist in load-carrying, rehabilitation and offer extra options in materiel-handling tasks. Today's powered systems tend to be slow, expensive, and have significant power requirements that constrain their duration of operation and range of viable uses. The unpowered mechanical systems that transfer load to the ground do not have the latter constraint, but they tend to disrupt the natural walking gait and have a lower load-assist capacity. Both system types are likely to entail user training requirements to ensure operator safety. Despite these challenges, continued improvements in this technology is likely to see its uses expand to assistance for the elderly, sick and injured, as well as regular use by soldiers to help with load-carrying and protection.

3.4 Materials and Manufacturing

The field of materials and manufacturing is vast, with emerging research in materials with new properties and applications. Apart from additive manufacturing, this report touches on some of the developments that may impact military and logistic applications, such as in protective materials, 'smart fabrics', structural alloys and glues, shape-shifting, biodegradable and self-healing compounds. An update is also provided on water generation technologies. Some examples of these technologies are illustrated in Figure 9.

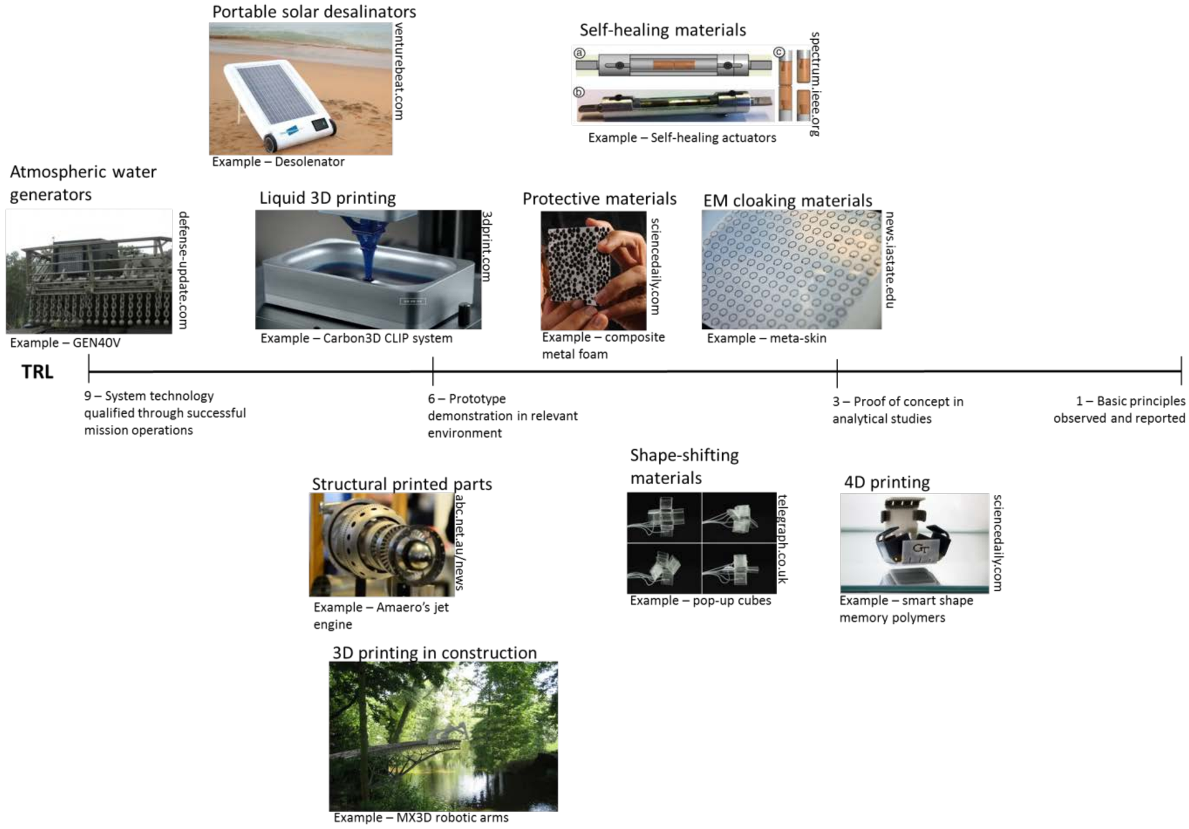


Figure 9   Emerging technologies in materials and manufacturing

3.4.1 Additive Manufacturing

While Additive Manufacturing (AM) development has largely been driven by the aerospace sector, it is now experiencing more widespread adoption for spare parts manufacturing, large-scale construction, customised production and prototyping, low-volume tooling, custom prosthetics and implants, and bio-printing. A summary of the well-established techniques and their key characteristics is provided in Table 1.

Practical uses in parts manufacturing and prototyping have been demonstrated with General Electric's (GE) and Amaero's printed jet engine designs [215, 216]. GE Aviation now routinely uses printed metal alloy nozzles for its LEAP (Leading Edge Aviation Propulsion) engine, reducing both the number of parts and total weight [217]. Similar considerations have seen Boeing adopt a large number of 3D printed parts within its airframes [2].

Basis	Technique	Materials	Advantages	Disadvantages
Liquid	Fused Deposition Modelling (FDM)	Plastics	• Variety of materials • No post-process chemical treatments • No curing	• Low z-axis resolution
Liquid	Stereolithography (SL)	Plastics: Photosensitive polymer (UV)	• High resolution	• Restricted material choice • Complexity of equipment
Liquid	PolyJet	Plastics: Photosensitive polymer (UV)	• High resolution	• Restricted material choice • Complexity of equipment
Powder	Selective Laser Sintering (SLS) / Direct Metal Laser Sintering (DMLS)	Various: plastics, metals, ceramics; combinations of materials; composites (e.g. polyamide with fibreglass), metal alloys	• Versatility in material choice • Ability to print metal alloys, composites and combined materials • Unused powder can be recycled • High-strength materials	• Limited by powder particle size • Inert gas may be required to avoid oxidation • Requires exact temperature control • Complexity of equipment • High maintenance
Powder	Selective Laser Melting (SLM)	Single-material metals or similar-material metal alloys	• Creates single-piece homogenous metal structures • Unused powder can be recycled • High-strength materials	• Limited to single-materials or similar-material mixtures • Inert gas may be required to avoid oxidation • Requires exact temperature control • Complexity of equipment • High maintenance
Powder	Electron Beam Manufacturing (EBM)	Metals	• Versatility in material choice, including pre-alloyed metals • Unused powder can be recycled • High-strength materials	• High voltages required • High vacuum required • Requires exact temperature control • Complexity of equipment • High maintenance
Powder	Laser Engineered Net Shaping (LENS)	Wide variety of metals, including: stainless steel, titanium, and nickel-based alloys.	• Versatility in material choice, including pre-alloyed metals • High-strength materials	• Complexity of equipment • High maintenance
Powder	3DP	Wide variety of polymers	• Variety of materials	• Complexity of equipment • High maintenance • Complex process
Powder	Prometal	Stainless steel	• Versatility in material choice, including prealloyed metals • High-strength materials	• High-temperature post-processing • High maintenance • Complex process • Complexity of equipment
Solid	Laminated Object Manufacturing (LOM)	Adhesive-coated paper, plastic or metal laminates	• No post-processing or supportive structures required • No deformation or phase change	• Subtractive technique increases wastage • Low surface definition • Complex structures difficult to build • Complexity of equipment

Table 1 Summary of established additive manufacturing techniques [218]

In the military context, the US DoD is now trialling several different concepts of employment for this technology. For example, the US Navy is now using AM to make tools, moulding, repairs and implants as part of its 'Print the Fleet' experiment [217]. They are also testing printed flight-critical parts for the V-22 Osprey aircraft [219]. The US Army Rapid Equipping Force (REF) is deploying mobile AM laboratories in Afghanistan in order to quickly prototype and manufacture required parts in the field. An example of successful application of this concept has been in development of metal covers for the Mine Resistant Ambush Protected (MRAP) Vehicle to prevent damage from rocks or fixed objects to the valve system. The entire process from design to quick fabrication took less than five weeks. Concurrent wheel redesign by the manufacturer was expected to take more than a year [217, 220]. The US Army is also trialling its Mobile Parts Hospital concept for instant fabrication of parts in a combat zone [217]. For health support, the US Army Medical Prototype Development Laboratory is able to quickly design, fabricate and deliver prototypes of medical equipment to the field using 3D printers. Examples of such products are collapsible lightweight litter stands and new water monitoring kits [220]. DST Group has also demonstrated successful use of supersonic particle deposition and laser cladding techniques for restoring aircraft parts, which has achieved substantial cost savings [218].

At the same time as adoption of existing techniques gathers pace, new approaches for faster, cheaper and more complex fabrication are being developed. Hewlett-Packard (HP) are now taking orders for their HP Jet Fusion printer that is claimed to be ten times faster than existing machines and able to print electronics through the use of conductive materials printed at the voxel level [221]. MIT's MultiFab system uses 3D scanning techniques to self-calibrate and self-correct and allows users to embed complex components directly into the body of an object [222]. Picatinny Arsenal in the US are using an inkjet printer to print electronic components such as antennas and fuse elements directly onto surfaces, with direct application in soldier-worn electronics [217]. Printable electronics and multi-component printing are being researched in the Netherlands [223] and the UK [224]. MIT researchers have demonstrated printing with glass [225].

One of the most interesting recent developments has been unveiling of Carbon3D's Continuous Liquid Interface Production (CLIP) technology. It uses a photochemical process by projecting light through and oxygen-permeable window into a reservoir of UV curable resin. The projected UV images solidify the part as the build platform gradually rises. The process is much faster than traditional 3D printing and the parts have consistent and predictable mechanical properties, although the range of materials is more restrictive. We are yet to see what impact this technology will have on the commercial markets [226-228].

Large-scale construction has been tried previously using giant cement 3D printers [10, 218]. However, a potentially more adaptable approach has been developed by MX3D in Holland, who are using robotic arms to do multi-axis 3D printing with both metals and resins in mid-air without supporting structures. The company has used this approach for a range of products from bicycles to bridges [218, 229].

Some scepticism about long-term potential of 3D printing persists with challenges in testing and certification, cost, intellectual property (IP) issues, speed of production and

energy requirements. Cyber security is also a concern, particularly for military operations. However, there are substantial reasons to expect globally transformational effects as thinking shifts from parts replication to complete re-design[14]. This trend is supported by its wide-spread adoption by educational bodies (schools and universities), facilitating further innovation in applications. For the military, AM can alter the nature of supply chains by shifting from transporting goods to moving design data and raw materials. It can serve to make military logistics more agile with smaller, more secure supply chains. Digital supply chains that use universal raw materials should be more resilient and easier to reconstitute. AM can be expected to reduce supply lead times, facilitate customisation and overcome parts obsolescence [217]. On a global scale, AM is likely to cause gradual changes in economic models and ecosystems and in social structures over the next 2-3 decades.

3.4.2 Novel Materials

Protective light-weight materials with high tensile strength have a lot of direct applications in the military for body armour and in platform and shelter construction. Several different approaches have been developed recently. The US Army is currently testing lightweight wallpaper lined with Kevlar fibres [230]. North Carolina State University researchers are working on Composite Metal Foam (CMF) with hollow metallic spheres embedded in a metallic matrix. It is lined with Kevlar and in tests, stopped a 7.62x63 mm M2 armour-piercing projectile with 8 mm indentation on impact [231, 232]. A different research project has demonstrated a syntactic foam metal matrix composite that can float on water. It not only protects from impact, but would not sink even with structural damage (e.g. if used in boat construction) [233]. At lower TRL are projects to use organohydrogels to create 'second skins' for chemical-biological protection [234] and DST Group's research into the use of shear-thickening fluids to create impact-resistant batteries [235]. A different type of protection is offered by cloaking materials that allow EM frequency tuning and protect objects from radar detection [236, 237].

The 'smart fabric' concept is gathering momentum in the US with the Pentagon now leading a major new initiative for mixing sensors into clothing to regulate temperature, detect biological threats, provide power or change colours [238]. In the meantime, researchers at the University of Exeter in the UK have created the first 'truly electronic' textile by embedding graphene electrodes into textile fibres [239]. Applications of this new textile process are yet to be explored.

New structurally strong materials have been created in Australia (corrosion-resistant light-weight alloy) [240]. In the US, researchers have produced stretchable nanofibers that are tougher than Kevlar [241]. In a somewhat unconventional approach, researchers in Italy fed spiders carbon nanotubes in order to generate even stronger versions of spider silk [242]. Unfortunately, there is no efficient way to harvest spider silk on an industrial scale.

[14] A lot of sceptical assessments of AM have been based on comparison of production efficiency and costs for existing parts using AM compared to traditional manufacturing techniques. In actual fact, the biggest potential of this technology is in the ability to make new designs that couldn't possibly be produced via traditional manufacturing. This trend is only just starting to develop and its long-term impact is near impossible to predict.

Interesting developments in adhesives include a CTC[15]-based glue that rivals mussel glue and works in aqueous environments, with potential applications in medicine [243], e.g. wound treatment. Researchers in Singapore have produced 'electric' glue that starts bonding when a small voltage is applied across it. It can set anywhere provided a voltage can be applied and hence has potential application in maintenance and repair, including underwater [244].

New effects have been demonstrated with shape-shifting materials [10, 245-247]. An example is 3D structures that sequentially fold themselves from components that are flat or rolled into a tube for shipment. They respond to stimuli such as temperature, moisture or light with smart shape memory polymers (SMPs) changing shape in a controlled sequence over time [245]. Future applications of this could be in reducing the volume of transported infrastructure and equipment, although no prototypes of this have yet been created.

Biodegradable electronics are becoming a more widespread idea as the volume of discarded consumer electronics rises. For the military, they have potential applications in the security of discarded devices. Examples include construction of chips on nanocellulose platforms [248] and heat-triggered self-destructing electronic devices [249]. The opposite effect is found in self-healing materials with the use of hybrid gels [250], Diels Alder polymers [251] and transparent resin [252]. Potential practical applications are vast, but are yet to be tested.

3.4.3 Water Generation Technology

Water generation technology has been highlighted as a valuable concept for military logistics with numerous examples given in the last two reports [1, 2]. It is now more widely adopted in other military forces with both the Israeli Defence Force and the French forces now using the WaterGen GEN40V atmospheric generators and Water Treatment Units within their armoured vehicles. The latter is actually designed to treat water generated within the vehicles' air-conditioning units [253]. In maritime, amphibious and coastal HADR operations, desalination technology such as Desolenator could be of interest. It is a low-cost portable desalination unit powered by sunlight, can process up to 15 litres of water per day, and is expected to operate for twenty years [10, 254].

An interesting approach for humanitarian logistics has been adopted by a non-profit company pAge Drinking Paper. The company has designed a book with pages embedded with silver nanoparticles. Each page has printed information on water safety in English and in local languages. Each page can be removed from the book and inserted into a special holding device into which water is poured. One page can clean up to 100L of drinking water and one book is expected to provide a person's water needs for four years [255].

[15] The Siderophore cyclic trichrysobactin material was invented by the same research team.

3.5 Sensors

Sensors are becoming more ubiquitous in all aspects of daily life, now giving rise to the popular concept of the 'Internet of Things' (IoT). This concept is also enabled by advances in technologies such as micro-electromechanical systems (MEMS), wireless communication and high-volume micro-scale manufacturing. The IoT can be expected to affect sectors as wide-ranging as transportation, energy, retail, agriculture, and city design. An example of this can be seen in Hamburg's 'SmartPort' project [256], whereas China is now making a deliberate, government-sponsored effort to develop machine-to-machine (M2M) services [257]. Increased connectivity is also bringing with it greater cyber-security risks, as was discussed previously. In military contexts, sensors have been predominantly used to get more accurate environmental monitoring and situational awareness, as well as developments in navigational applications. Some specific examples of relevant sensor technology are given Figure 10 and discussed below.

3.5.1 Biometrics

Use of biometrics for security has come under scrutiny recently as technology has evolved to enable, for example, replication of fingerprints from photos. Consequently, more advanced systems continue to evolve, such as a fingerprint scanner that not only captures a 3D image of a fingerprint, but also the structure of the tissue below it using ultrasound [258]. In addition, developments continue in rapid mass surveillance. An example of applicable technology is the iris scanner developed at Carnegie Mellon University that works at up to 12 metres (noting that these types of scanners are still fairly easy to evade with use of glasses or hats [259].)

3.5.2 Laser Sensors

Laser sensors have become widely used in driver-assist technology, although their cost is still significant with respect to the cost of such vehicles. An example of technology that aims to reduce this cost is Quanergy's solid-state LIDAR[16] that has no moving parts, can scan in every direction and is expected to cost under US$1000 when commercialised [260]. For military applications, technologies such as DARPA's Sweeper[17] comprises a LIDAR-on-a-chip that uses a phased array mechanism to sweep 100,000 times a second. This is approximately 10,000 times faster than current LIDARs. Although it has a more restricted field of view than rotating 360 degree cameras, it has the potential to significantly improve machine navigation in complex environments [261, 262].

[16] Light Detection and Ranging
[17] Short-range Wide-field-of-view Extremely agile Electronically steered Photonic EmitteR

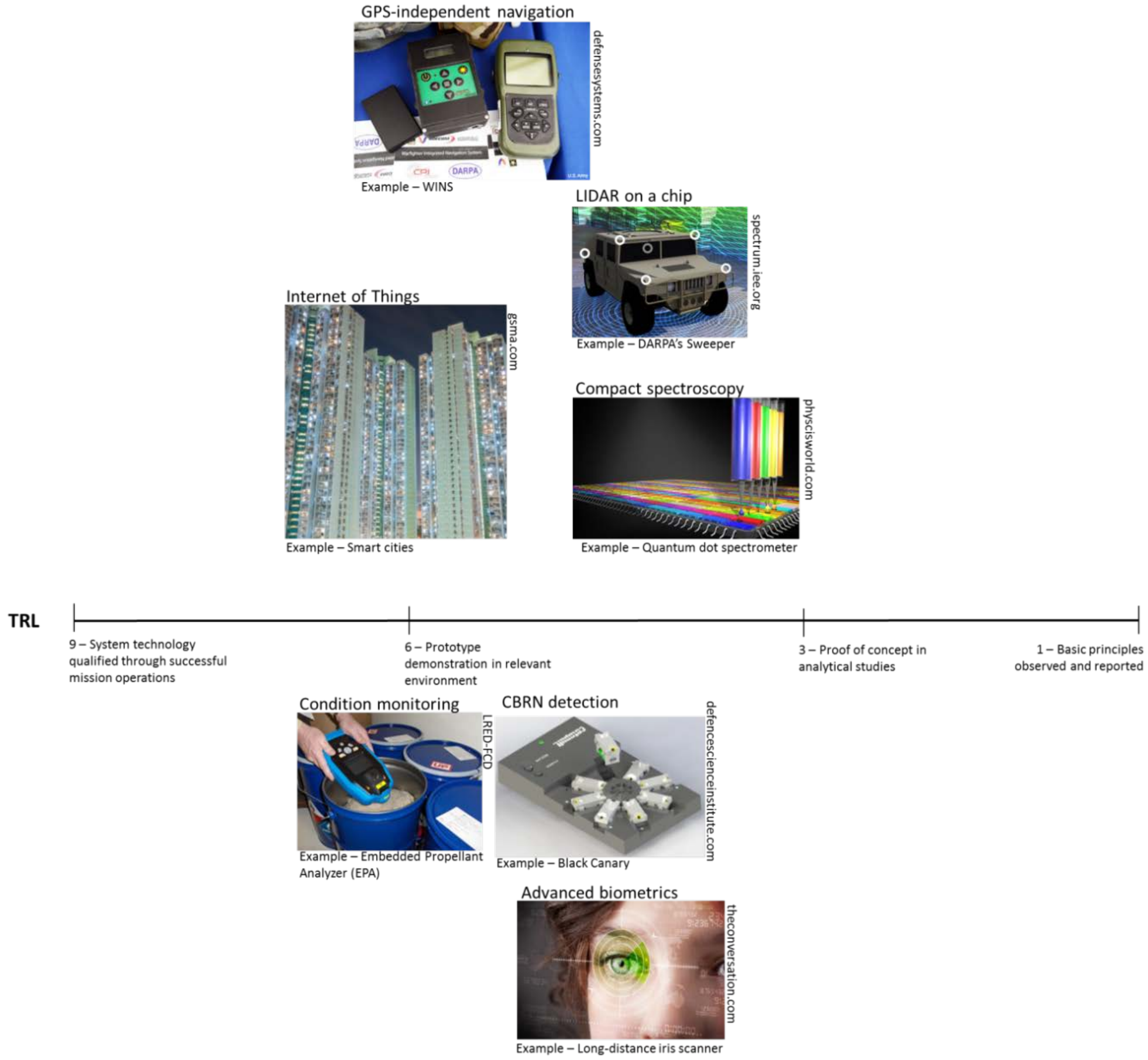


Figure 10 Examples of emerging sensor technology

3.5.3 CBRN detection

Research into more effective CBRN detection continues, even as CBRN sensors are already incorporated into deployed unmanned systems. Examples of the latter include the Multi-Agent Tactical Sentry (MATS) used by the Canadian Forces [263], Qinetiq's Talon and iRobot's Packbot [15]. All of these UGS have CBRN reconnaissance capabilities. Canadian Forces also use unattended ground sensors such as the VP BioSentry[18] [264].

Some developments in supporting technologies have been demonstrated in the use of compact laser diodes [265] and Resonance-Enhanced Desorption Ionization in the REDIchip [266, 267]. DST Group has developed a prototype of its Black Canary device, which is designed to be an early warning system for users, but can also communicate with other devices in the area for more complete information picture [268].

[18] Vital Point Biological Agent Detection, Sampling and Identification

3.5.4 GPS-Independent Navigation

As the threat of satellite warfare undermines trust in ubiquitous availability of accurate satellite-enabled navigation, research continues into GPS-independent navigation systems. Currently available inertial-based solutions continue to exhibit a significant degree of drift over time, although optical-flow techniques mitigate this to some extent.

The US Communications Electronics Research Development and Engineering Center (CERDEC) is developing the Warfighter Integrated Navigation System (WINS) that uses INS sensors similar to those in smart phones to track soldier movements [269]. DARPA is working on a more accurate technology, including sensors that operate under high dynamics, sensors that self-calibrate, fully integrated miniature timing and inertial measurement units, and miniature atom-based inertial sensors for extended operation [270].

3.5.5 Condition-Based Maintenance (CBM)

As has been previously reported, CBM has been effectively adopted in the aerospace industry and is gaining ground in commercial vehicles for mining and general consumer use [1, 2]. Military organisations such as US RDECOM are now interested in developing integrated sensor suites to monitor temperature, humidity, 3-axis shock and vibration for monitoring stores such as ammunition [151]. In addition, the same organisation is looking at using handheld Raman spectroscopy devices for propellant monitoring [151].

Accurate and non-destructive testing is required in quality control applications for pharmaceuticals and food. An example of technology that seeks to address this challenge is the Q-Eye sensor developed at the University of Warwick. The prototype uses a sensor that can detect radiation in the Terahertz region. This allows it to detect the rise in temperatures produced when the EM radiation emitted by an object is absorbed by the sensor, down to very small packets in quantum energy. While still at prototype testing stages, this technology promises to be cheaper, more sensitive and quicker than existing sensors of this type [271].

3.6 Information and Communication Technologies

Digitisation of all aspects of life has given rise to new concepts like the Internet of Things, Big Data and cyber-warfare. Along the way, this has continued to increase the requirements for data transmission, storage, analysis and security. These enabling technological developments have, in turn, produced new and challenging phenomena such as artificial intelligence, the impact of which is yet to be understood. Some examples of emerging ICT are shown in Figure 11.

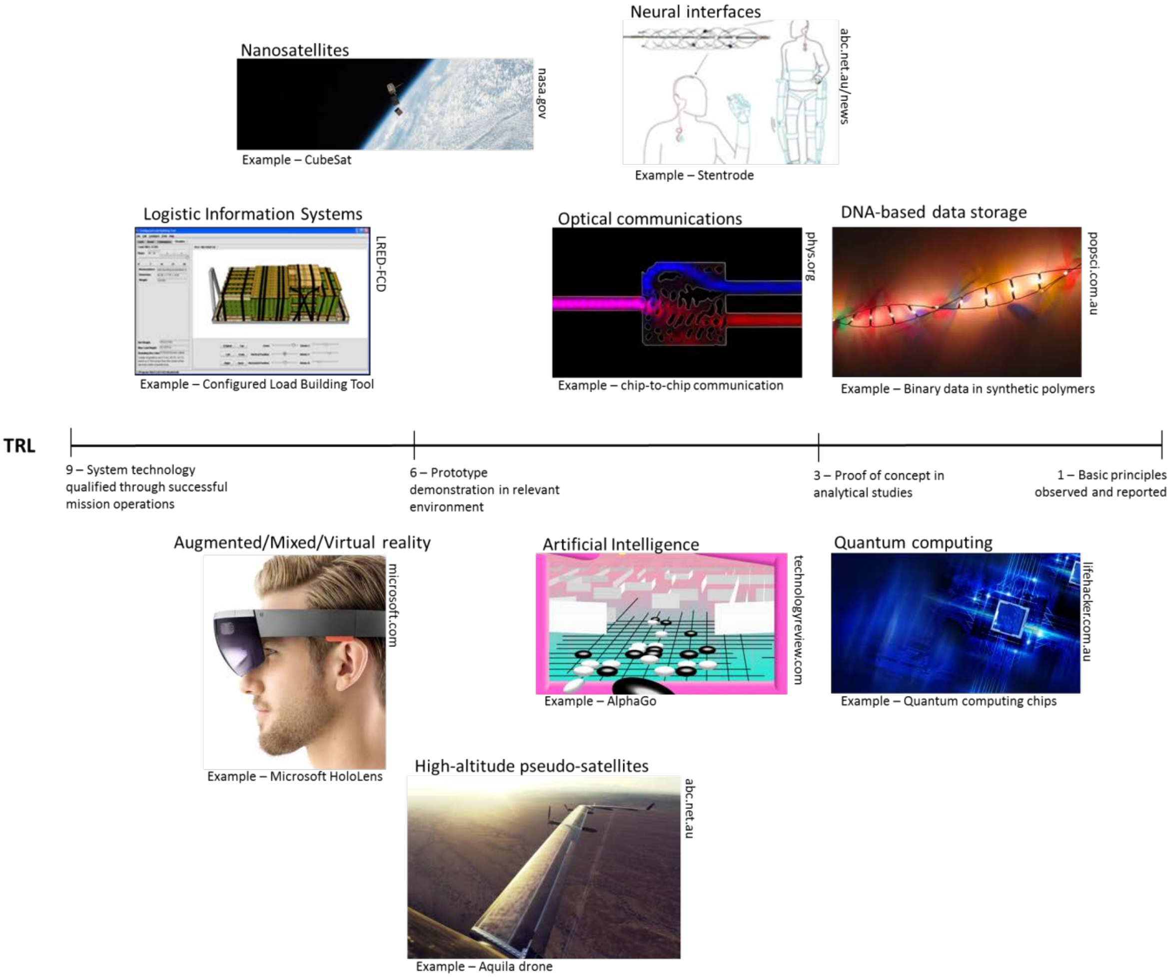


Figure 11 Emerging information and communication technologies

3.6.1 Alternative Computing Approaches

One of the better publicised research directions in novel computing approaches has been quantum computing. In classical computing, numbers are represented as ones and zeros. Algorithms are then used to manipulate them so as to transform input into output. In quantum computing, atomic-scale units (qubits) can exist in a state of 'superposition' – be simultaneously zero and one. This means that a single qubit can be used to perform two separate streams of calculations in parallel, giving better computational efficiency [272].

Some of the key areas of research in this field include quantum computers (discussed here), quantum sensors, and quantum communications. These technologies are largely at TRL 3-4 with various devices being built to demonstrate the fundamental operational principles. Significant challenges for quantum computing include the tendency to accumulate errors. These may be mitigated by error correction codes, but at the cost of an overhead in qubits. Qubits are also difficult to manipulate, as any disturbance causes them to fall out of their quantum state or 'decohere'. This makes quantum computers difficult to build and no provably fully functional computers exist as yet. Current techniques for

creating qubits work on a small scale, but do not scale up well. Some verification challenges lie in the probabilistic nature of the output and in the fundamental quantum mechanics principle that observing a quantum particle changes its behaviour [273].

If successful, however, this technology is expected to have a significant impact in the areas of communications, sensing, navigation and guidance systems, clocks, resource exploration, hazard detection, computing, and understanding of biological processes. Quantum communications may provide a range of applications for information security. Clocks using quantum technology can improve resilience of networks when satellite signals are lost. At the same time, there is potential for disruption in data security systems, as conventional encryption techniques may become obsolete [272, 273].

The most promising approaches for building quantum computers so far include the use of photons, ion traps, superconductors, quantum dots and single donors in silicon. The latter is the focus of research for the Australian Centre for Quantum Computer and Communications Technology (CQC2T), which is one of the leading research bodies in this field [273]. MIT researchers have developed a computer from five atoms in an ion trap with laser pulses that is designed so that more atoms and lasers can be added later [272]. A Swinburne University of Technology team has demonstrated entangled photon states with greater complexity and multiple channels on an integrated chip [274]. In the Netherlands, a nanoscale device was demonstrated that can 'sculpt' individual light photons on demand, whereas researchers at NASA have successfully teleported information about the quantum state of a photon over 15 miles of optical fibre [10].

Neuromorphic computing aims to mimic some of the processes that occur in the human brain with the use of synaptic chips that offer substantial increases in speed, density and power efficiency over conventional computer chips. This makes them suitable for certain types of supercomputing applications, but potentially also in robotics, voice recognition, driverless cars, UAS and smartphones. They do, however, require an entirely new operating system and application software if they are to be generic and programmable.

Researchers in the US have created custom hardware using a non-conventional compiler, a neuromorphic architecture and a space-efficient microarchitecture to create a neuromorphic computing system designed for energy-efficient evaluation of large-scale neural networks [275]. In Australia, a hardware chip has been built that has the ability to learn autonomously, evolve and associate information and respond to stimuli like a brain. Unlike the current systems that constitute hardware that executes software, the new chip is a hardware-only solution that researchers claim to be 5000 times faster at 1/1000th of the power requirements of conventional systems [276]. Neuromorphic computers are more advanced than quantum computing or DNA computing, with some systems now at TRL 5-7. Whether they make a substantial impact in replacing conventional systems remains to be seen.

3.6.2 Artificial Intelligence

Demis Hassabis, the founder of Deep Mind, describes AI research aims as 'solving intelligence, and then using it to solve everything else" [277]. Applications for AI span

across most industries, with the promise of fast and accurate decision support and tactical planning. On the other hand, AI systems are less able to deal with inherently complex situations. Some concerns have been raised by prominent thought leaders such as Stephen Hawkins and Elon Musk on the potential dangers of AI gaining control over critical systems. In the military context, the risk of 'flash wars' has been flagged, where AI-led tactical choices might lead to conflict escalation that happens too fast for human control[19]. Maintaining 'human on the loop' in these types of decisions has been one of the guiding principles of military AI development. This principle may be tested in situations where split second decision-making offers significant tactical advantage. There are also philosophical and ethical questions around what it means to be human and around AI concepts of employment.

In 2011, Demis Hassabis founded DeepMind with the aim of learning how to transfer biological knowledge to machines. The company initially developed software that learned to play Atari games in 2013. Following its acquisition by Google in 2014, it unveiled the existence of the AlphaGo AI in 2016. This AI proceeded to beat arguably the world's best Go player in March 2016 – a milestone that is significant because of the incredibly large numbers of possible permutations arising from each move. The company now continues to work on creating AI that can learn to take on any task. The programme uses reinforcement learning with rewards and punishments. It also uses systems for evaluation of possible moves and a search mechanism for selecting those that look most promising. This is combined with the 'deep learning' method that has recently delivered advances in machines' ability to decode information such as in image recognition [277].

Other big players in AI research include Apple, who are aiming to put an AI assistant into every device. The company has recently developed its next generation voice-based AI assistant called Viv that will replace Siri and incorporates dynamic programming approaches [278]. IBM is looking at adding new AI techniques such as deep learning to the commercial version of Watson [279]. An example of a commercial application for AI is the system developed by Google that relies on simple video combined with machine learning and deep neural networks for pedestrian detection in self-driving cars [280].

An effective demonstration of potential AI uses in the military context has been recently carried out in the US. An AI called ALPHA (developed at the University of Cincinnati) was tested by experienced pilots in a high fidelity flight simulator. The AI was able to consistently defeat the human experts even when deliberately handicapped in terms of speed, turning, missile capability and sensors. The computing power required for the AI was equivalent to that of a low-budget PC. The researchers are now looking to develop it into a 'teammate' for air operations [281].

3.6.3 Data Storage and Security

The major new direction in data storage research has been in the use of DNA material. DNA can fit petabytes of information into a drop of liquid and survive for more than 100,000 years under the right conditions. Currently, the biggest challenges include the time

[19] Think of the recent troubles caused by automated trading systems in stock market trading

it takes to encode a meaningful amount of information (days for several megabytes), time to decode (hours for comparative amounts) and a lack of searchability [282]. These limitations mean that this method is currently primarily being assessed for long-term archival storage. A few different approaches are being explored, although the research is at relatively low TRL and none of the systems are mature enough for commercialisation.

Along similar lines, Harvard researchers have reduced a digital file into binary and then matched that binary to DNA bases. They were able to encode 10 MB to a DNA sequence and then decode it later within several hours [282]. Researchers in Switzerland have demonstrated encoding of DNA with 83 kilobytes of text in a stable process [283]. A French team has taken on a different approach by building binary data into a strand of synthetic polymer. The monomers were assigned to represent zeros and ones. The polymer was built by stringing monomers in a specific order and a mass spectrometer was used to read the data. The storage material mass using this technique is approximately 100,000 times less than using e.g. cobalt alloy. However, at this stage, only a handful of bytes of information have been chained together [282].

Data security continues to be a race against the ever-evolving cyber threats from state and non-state actors, with quantum communications now also offering some of the most promising directions for secure data transmission. Quantum communication systems that provide secure communications over limited distances are already being commercialised in Australia (Quintessence Labs), the US (MagiQ), Switzerland (id-Quantique) and France (SeQureNet). Further research is being carried out by Toshiba, HP, IBM, Mitsubishi, NEC, Nippon Telegraph and Telephone (NTT) and Chinese government organisations. Specific areas of research include quantum fingerprinting, quantum seals, authentication of quantum messages, quantum anonymous transmissions and quantum digital signatures [273]. The problem of distance is being addressed via quantum repeaters and/or noiseless amplification. Additional challenges are presented by techniques such as quantum key distribution (QKD) is that it still doesn't address authentication standards and that a full certification process is yet to be developed [273].

Ironically, quantum computing also threatens obsolescence to certain types of encryption protocols, such as those that rely on factoring as a hard-to-invert problem [272]. Queensland University of Technology researchers are looking at address this through development of a new quantum-proof version of the Transport Layer Security (TLS) Internet encryption protocol It incorporates a fairly recent mathematical technique called 'ring learning with errors problem' that researchers believe may be resistant to quantum attacks [284].

In the meantime, MIT researchers have developed a new system called CodePhage that addresses some of the current problems in software development. Essentially, it repairs software bugs by automatically importing functionality from other, more secure applications, achieving a reduction in time and effort spent by software developers in performing security checks [285]. Although, in what is a constant game of cat and mouse, the bug-fixing software itself may be open to cyber-attacks and subversion.

3.6.4 Data Transmission

One of the most interesting and potentially transformative developments in the area of data transmission recently has been the emergence of 'ubiquitous connectivity' as a practically achievable concept. It is enabled by parallel developments in UAS technology and alternative energy sources, as well as laser and optical communications. An example of this is Facebook's recent demonstration of its solar-powered Aquila drone. The drone has a wingspan similar to a Boeing 737 (42 m), weighs about 400 kg and is designed to hover between 18,000 and 27,000 metres (above the altitude of commercial planes and above weather). It can fly for up to 90 days at a time and was developed in order to expand internet access across the world[20] [286-289].

Similar concepts could be applied to enabling localised military communications networks and persistent surveillance. This idea is being explored by UK Ministry of Defence (MoD) who have recently purchased the Zephyr solar-powered UAS developed by QinetiQ. The UAS is designed to keep flying for months and is expected to deliver ISR and possibly mobile communications capabilities [290]. Other research continues in the use of UAS/UGS to provide satellite-independent communications on the battlefield. This may be a UAS operating overhead used as a repeater between low power terrestrial communications to satellites, or air-droppable radio repeaters that are dispersed to provide coverage across the area of operations. Pre-positioned systems can be discrete and activated only when needed. They may be used to improve or provide line-of-sight communications for radio connections and provide improved radio power and endurance while reducing the burden and risk on the soldiers.

Looking even higher, a number of companies are now looking at the use of very small satellites for connectivity and other purposes. Perhaps the largest of these projects is the OneWeb project. The company contracted Airbus to build the world's largest satellite constellation with 900 spacecraft (600 to be launched, the rest held as spares). The project envisages 20 planes of satellites in the sky connecting to small terminals on the ground. These terminals would then link out to local phone networks and web-hubs, providing ubiquitous connectivity across the world. The venture is still in its early days and no launches are envisioned before 2018 [291]. On a smaller scale, though, NASA has already demonstrated the launching of 'CubeSats' for the testing of laser communications and formation flying [292], and the US Army have developed and tested a nanosatellite that provides voice and data [293]. The latter has been described as 'a cellphone tower in space, except … it's for Army radios'.

Visible light communications remains an area of interest as a potential alternative to Wi-Fi. The key advantage of 'Li-Fi' is speed, with theoretical speeds of over 200 GB/s or 100 times faster than Wi-Fi which uses radio waves to transmit data. Light has limitations as it can't travel through walls or structures, although this may work well in places where Wi-Fi is restricted and privacy is desired (e.g. in schools and hospitals), and in particular in

[20] Facebook have also completed testing of a new laser, as part of a laser communication system, capable of transmitting 10GB/s and connecting to a point the size of a small coin 10 miles away.

military environments where secure wireless communications within a restricted area is required.

Although this type of communication is not yet mainstream, prototype technologies are already being developed. A French company, Oledcomm, has demonstrated Li-Fi technology within a smartphone that uses LED bulbs (which flicker on and off thousands of times a second) to beam information through the air like a digital Morse code. Apple are now looking at integrating this technology into their smartphones [294]. Some supporting technologies have been developed in the US with novel polarisation of laser light [295] and optical communications at the nano-scale [296]. IBM have designed and tested a fully integrated 'wavelength multiplexed silicon photonics chip' which will soon enable manufacturing of 100GB/s optical transceivers. This will allow data centres to offer greater data rates and bandwidth for cloud computing, big data applications and bulk data transfer [297], with reduced power requirements.

3.6.5 Interfaces

The technology for augmented, mixed and virtual realities (VR) is now becoming widely used. In the commercial sector, this has been largely driven by the entertainment industry with major VR headset makers now releasing consumer VR sets such as Oculus Rift, HTC Vive and PlayStation VR. Previously reported augmented reality systems such as Microsoft HoloLens and the Vizux systems [2] have more direct applications for logistics in providing efficiencies in warehouse operations and enabling tele-assistance. Systems such as HP's Zvr use a 3D monitor and precise head tracking and digital pen technology to create virtual holographic 3D images. The user can manipulate these images to explore data in three dimensions, which is useful in data analysis applications [10]. NASA and DARPA are testing a telepresence system for control of Robonaut, which conducts repairs on the International Space Station [298, 299].

Similar technologies are now increasingly used in new military platforms. In Israel, the ScreeneX touch-screen bullet-resistant windshield has been developed. The touch-screen device is inserted between the safety glass layers and the screen is connected to the vehicle multimedia system [300]. DARPA's GXV-T programme described in Section 3.2 will also include Honeywell's VR instrument panel to replace glass windows. The display system will project a wide-angle, high-definition 360 degree view of external conditions [301].

Looking further ahead, one of the most interesting emerging research directions has been in direct neural interfaces. This research is of interest to medical professionals for enabling more natural control of advanced prosthetics. However, there has also been some interest from the military community in developing more fluid integration of human-machine teams [15]. A project that spans both areas is currently being carried out at the Melbourne Royal Hospital (with DARPA's funding). The research team has developed a 'stentrode'[21] the size of a paperclip that would act as a 'brain modem'. It sits inside a blood vessel next to the brain and records brain activity, which is then converted to electrical commands. Tests have shown effective control of bionic limbs and trials are planned in spinal cord

[21] Electrodes incorporated into a stent

patients in 2017. It is not yet clear whether the stentrode can record the kind of high fidelity data that DARPA is seeking [302, 303].

3.6.6 Logistic Information Systems

Logistics Information Systems (LIS) continue to expand their functionalities in terms of risk-management, optimisation and visibility of supply chains, with many upgrades taking place in military logistic systems. This includes US Army's Global Combat Support System – Army (GCSS-Army) which was fielded to 14,000 users at 281 supply nodes in 2015 [304]. The US DoD Logistics Modernisation Programme (LMP) went live in 2003 with phased roll-out and eventual retirement of legacy systems in 2014 [304]. Examples of supporting systems in the US military logistics architecture include Logistic Support Activity (LOGSA) Information Technology Services [304], the Configured Load Building Tool (CLBT)[22] [151] and Fleet Insight Toolkit (FIT) [305]. The latter turns wheeled vehicle usage and health data into actionable information for unit maintenance.

The UK MoD are now using the Logistic Functional Area Services (LogFAs) capability and its new version, LOGFS, which provides a suite of logistic tools and applications to assist with planning, execution and sustainment during deployments [305]. The Canadian Armed Forces have designed a sense-and-respond logistic decision support capability prototype to handle dynamic complex supply chain management problems, enhance supply chain visibility, optimise the supply chain, provide shared situational awareness, self-synchronisation and faster speed of execution [305]. The ADF are now looking to replace its Military Integrated Logistic Information System (MILIS) with SAP-based software.

While these systems promise substantial advantages in terms of situational awareness and supply chain optimisation, the LMP example shows the difficulties involved in effective large-scale adoption. This system went through a phased roll-out and development over many years, with further iterations required as additional requirements emerged.

3.7 Health Technologies

Technological advancements for health-related applications are wide-ranging and many that are mentioned here overlap with other technology types. An example is the use of unmanned systems for casualty evacuation (CASEVAC) tasks and employment of robots in surgery. Various sensors are now assisting with wide-spread health-state monitoring and neural interfaces play a role in development of advanced prosthetics. Advanced manufacturing techniques such as 3D printing and flow manufacturing are being adapted to health tasks. On a more specialised side, new compounds and devices are being developed to assist with initial casualty management and diagnosis. Looking further ahead, breakthroughs in genetic manipulation techniques, such as CRISP-R[23] promise a range of new possibilities in research and treatment options. In the military context, this

[22] In development
[23] Clustered regularly interspaced short palindromic repeats

technology may present a source of threat with easier construction of dangerous biological agents. Some examples of these technologies are shown in Figure 12.

3.7.1 Autonomous CASEVAC

Although evacuation of battlefield casualties via unmanned systems has been considered before, a lot of reservations have existed about its use in terms of both medicolegal and human factors. However, this concept presents the advantages of potentially faster evacuation from dangerous areas without risking additional personnel. For these reasons, NATO now considers this type of evacuation acceptable in some circumstances [306].

Examples of systems for this purpose include the REV (Robotic Evacuation Vehicle) and REX (Robotic Extraction Vehicle) 'marsupial' pair developed in the US [15]. REV is essentially an unmanned ambulance vehicle that carries REX – a small stretcher bearer that can drag the wounded soldier into the ambulance. REV has a life-support pod with flat screen TV for communication with the casualty. Other efforts in this space include DARPA's ATLAS project [307] and the Battlefield Extraction Assist Robot (BEAR) [308]. These systems are not yet deployed and further R&D is required to make them practical at a tactical level. Robustness of communications remains a limitation, especially if line-of-sight communication cannot be guaranteed. Specific concepts of employment for different types of casualties have not yet been refined.

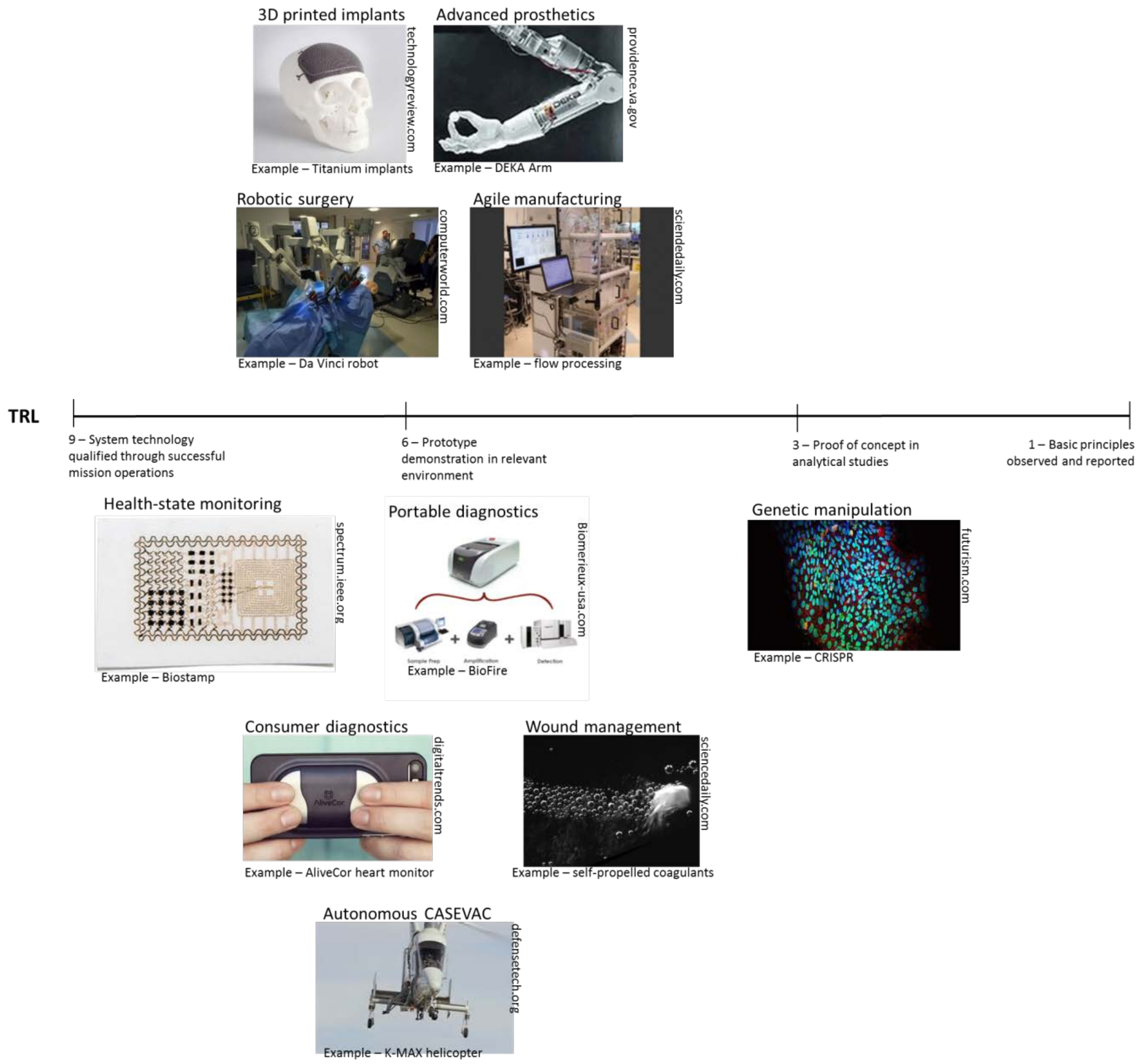


Figure 12 Examples of emerging health technologies

3.7.2 Initial Casualty Management

Research work continues into systems that help stabilise wounded soldiers so as to extend the window for evacuation prior to definitive treatment. Previous reports mentioned new agents and devices to assist with the management of uncontrolled haemorrhages [1, 2]. Further work has been done in developing compounds such as chitosan sprayable foam that has been shown to significantly reduce blood loss in animal trials [309]. Canadian researchers have created self-propelled particles that can traverse against severe blood flow (such as that seen in damaged femoral artery) to deliver coagulants [310]. Case Western University researchers have looked at pairing clot-promoting nano-particles with a corticosteroid to help reduce bleeding in lungs damaged during explosions, with some good results in animal tests [311, 312].

3.7.3 Robotic surgery

Robotic surgery has become main-stream for specific procedures. For example, the Da Vinci robot is now commonly used for prostate, gynaecological, head, neck and complex hernia repairs as well as heart bypass procedures. Hundreds of thousands of surgeries are now performed using this system each year across the world [313, 314]. Other examples of robotic systems include the Smart Tissue Autonomous Robot (SMART) for stitching [315], Flex Robotic System and Flex arm for operating through non-linear winding paths (like the throat) [314], and the Accuray CyberKnife Robotic Radiosurgery System for treating tumours [314]. Even for largely autonomous systems, it is still expected that the surgery will be closely supervised by a human specialist who can step in if necessary.

An example of a more specialised system is the VenousPro (by VascuLogic) [185, 316], an automated venipuncture image-guided robotic device for automated cannulation. Virtual Incision Corporation have taken a different approach and are developing a miniaturised surgical robot that can be placed entirely within the abdomen to perform specific types of abdominal surgery [317, 318].

Tele-surgery applications have been investigated at the Florida Hospital where researchers successfully tested the impact of the small time lag created by the Internet for a simulated robotic surgery 1,200 miles away [314]. The key risks were highlighted at around the same time as hackers demonstrating the hijacking of a robotic surgery procedure. This risk is likely to be significant in the military context, where robotic surgery may be eventually used to project certain types of surgical capabilities further forward without deploying surgical specialists.

3.7.4 Diagnostics

There is a great interest in developing effective portable diagnostic devices, as evidenced by the establishment of challenges such as the Qualcomm Tricorder Xprize competition. The current goal of the competition is to create devices that can diagnose 13 conditions ranging from diabetes to urinary tract infections [319, 320]. A whole range of miniaturised portable diagnostic systems have been commercialised with the advent of enabling technologies such as microfluidics.

Oxford Nanopore in France have developed a variant of the Oxford next gene sequencer (MinION) that is small enough to run on a USB connection. It has been adapted to detect all gene sequences in a blood sample, remove the human gene and leave all pathogen sequences for analysis [321, 322]. The Biomerieux company in the US sells the BioFire multiple Polymerase Chain Reaction (PCR) film array that integrates sample preparation, amplification, detection and analysis with a one hour turn-around time. The US Food and Drug Administration (FDA)-approved panels for this device include Respiratory, Blood Culture Identification, Gastrointestinal, and Meningitis/Encephalitis Panels covering over 100 pathogens in total [323]. Rutgers University researchers have demonstrated a microfluidics 'lab-on-a-chip' device that is smaller, cheaper and faster than conventional laboratory tests, as well as being networked [324].

Most existing systems only cover a limited range of pathogens. Harvard's VirScan test offers a new capability to test for thousands of past and present infections simultaneously. The test references a library of almost 100,000 synthetic protein fragments representing a section of a pathogen. The system is not yet at the commercialisation stage and some questions have been raised about the comprehensiveness of the viral history that it produces. However, long-term applications are likely to be found in research and vaccine development [325].

Miniaturisation of other diagnostic instruments can be seen in the development of the 'battlefield MRI' (Magnetic Resonance Imaging) system at the Los Alamos National Laboratory in US. The machine makes use of 'ultra-low' magnetic fields and an extremely sensitive magnetometer to provide images of comparative accuracy. It is lightweight and has low power requirements, although the shielding coils need further work to cancel out additional interference (such as from nearby metal objects) [326]. Some interesting smartphone-based diagnostic tools include the Portable Eye Examination Kit (PEEK) lens adapter to the smartphone's camera, the Oto device that turns an iPhone into an otoscope, and the AliveCor Heart Monitor that produces a personal electrocardiogram [319].

As discussed in the previous horizon scanning reports, these technologies offer significant gains for combat health support units in extending specialist diagnostic support further forward and to more dispersed nodes, as well as by reducing logistic footprint in eliminating the need to deploy large pathology laboratories and specialists. They also enable the telemedicine approach to specialist health care.

3.7.5 Health-State Monitoring

Health-state monitoring devices have become a popular type of consumer electronics with more and more people using them to assist with training, fitness and general well-being. Examples of biometric gadgets used by elite sportspeople for training include the Readiband to measure sleep quality, Motus Sleeve for tracking arm motion, Myontec Mbody Pro for measuring leg muscle imbalances and BSX Insight that monitors lactate levels. OtimEyeS5 is a popular app that accurately records a player's movement on the field or court [327]. More common consumer devices include FitBit and various smartphone add-ons. The Chem-Phys patch developed at the University of California helps monitor both biochemical and electrical signals in the human body [328].

An interesting approach has been demonstrated by researchers at the University of Illinois in the development of Biostamps. These circuits are stretchy and flexible like skin, collect power wirelessly and can be worn anywhere on the body. Different functions require different sensors with applications such as monitoring UV exposure, using sensitive dyes to detect chemicals in sweat, or electronically measuring blood pressure. Other uses include measuring skin hydration, wound healing, and delivering medications. Biostamps are about to undergo human trials in the US and Europe and units that communicate with Android smartphones have already been created [329].

It is possible that the proliferation of self-monitoring devices will help collect statistics into powerful databases, allowing prevention or prediction of health problems as well as

treatment success or failure [330]. For the military, monitoring of training and physical performance of soldiers may enable improvements in training outcomes, early problem detection and custom training regimes.

3.7.6 Advanced Prosthetics

Prosthetics have been greatly enhanced by advances in 3D printing, sensors and interface technologies. Ivan Owen's 3D printed prosthetic hand design was inspired by an 1845 design developed in Adelaide. It is low cost and now freely available [331]. Neural control of prosthetics has been demonstrated at the John Hopkins Applied Physics Laboratory [10] and at Caltech [332, 333]. The 'stentrode' device developed in Melbourne was described in Section 3.6.5. In an example of sensor-enabled developments, scientists have developed an ultra-thin silicon nanoribbon that includes sensors for detecting strain, pressure, temperature and humidity. This material may enable creation of artificial skin for prosthetics [10]. In the context of military health support, these types of technologies are likely to become a part of the rehabilitation process.

3.7.7 Advanced Manufacturing

Various novel manufacturing techniques have found their uses in health care. 3D printing is now commonly used to create customised (usually titanium) bone replacements [334]. A more complex approach involves bio-printing the organs themselves. Some success has been achieved with printing skin [220], the creation of mechanically-reinforced tissue constructs [335] and creating human ears for transplantation [218].

A different type of manufacturing is the flow processing manufacturing of pharmaceuticals, which MIT researchers have used to replace traditional batch production. The current prototype is the size of a bar fridge and can produce four compounds formulated as solutions or suspension with up to 1000 doses per day. The required reactions take place at temperatures up to 250 ^{0}C and pressures up to 17 atmospheres in the first module. The crude drug solution is then purified by crystallization, filtered and dried in the second module. It is then dissolved or suspended in water and checked using an ultrasound monitoring system [336]. While still limited in terms of the range and type of compounds it can produce, these types of systems can potentially give greater flexibility in responding to demand surges and for making low-usage 'orphan' drugs on demand.

4. R-TAF Based Assessment for Technologies of Interest

The Rapid Technology Assessment Framework (R-TAF) approach is a rapid, high-level decision support framework that considers the usefulness of new technologies for military logistic operations, their relative benefits compared to existing options, and the likely cost of developing an associated capability. It is described in detail in Appendix H. A number of technologies across the seven technology groups have been identified as potential technologies of interest in the previous horizon scanning reports [1, 2]. They were analysed using the R-TAF approach in order to form recommendations for further research or medium-to-long-term watch. An update for the previously identified technologies and recommendations is provided in Section 4.1. Section 4.2 provides a more detailed look at two new technologies.

4.1 Updates on Previously Identified Technologies of Interest

Table 2 Update on previously identified technologies of interest

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
Power and Energy			
Hybrid generators	Pilot trials and comparative assessment is recommended due to the maturity of the technology.	Hybrid generators that use conventional fuel, solar panels and batteries have been incorporated into the Hybrid Energy ITV (Internally Transportable Vehicle) Trailer (HEIT). US DoD developed and demonstrated HEIT in 2014. It is intended to provide a Company Landing Team with a highly mobile, MV-22 Osprey transportable electric power solution that is matched to energy demands and works with various energy sources. The system provides 3kW sustained power, surge to 4kW and uses 10kWh rechargeable batteries. It uses 1 jerry can of fuel per hour and runs at 70 decibels [338].	Opportunity for leveraging off systems developed and tested by allied nations.
Exportable Vehicle Power Systems (EVPS)	Cost-benefit analysis and close watch for energy saving opportunities is recommended.	N/A	N/A
Direct Current (DC) power microgrids	Cost-benefit analysis and close watch for energy saving opportunities is recommended.	N/A	N/A
Advances in battery designs	Close watch is recommended with a view to replacing existing batteries in military equipment once the technology becomes commercially available. Longer term watch is also recommended for these developments as enablers of potential conversion to all-electric vehicles for military platforms.	Improvements in power and energy density, alternative designs, miniaturisation, and increasing adoption of home-storage batteries. The latter is now starting to impact traditional grid-based electricity suppliers. [31, 32, 34-39, 41-54]	Closer watch now recommended as enablers for conversion to all-electric vehicles, more extensive employment of small UAS and sensors, and alternative power generation and storage systems.
Solid Oxide Fuel Cells	Wide-ranging conversion to this type of technology is a costly and complex exercise that requires careful assessment of impacts and a cost-benefit analysis. It may be a natural development if conversion to natural	Improvements in electrolyte materials, miniaturisation for use in small electronic devices, and alternative designs of fuel cells more generally (e.g. with use of microbes). Hydrogen fuel cells have been demonstrated in small UAS, extending their range ten-fold. [65-67, 71-	Consider previous recommendation in the context of declining liquid fuel security in Australia.

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
	gas occurs on a national scale. Infrastructure requirements include fuel (natural gas) transportation and delivery mechanisms. Further assessment is warranted due to high availability of natural gas in Australia.	75]	
Supercapacitors	Long-term watch is recommended for the important advances in supercapacitor technology to maturity and progress through to commercialisation. It is particularly pertinent to keep watch with respect to commensurate maturation of energy scavenging/harvesting technologies.	Use of new nanomaterials in electrodes, new manufacturing processes, incorporation into fabrics, miniaturisation. [55-64]	N/A
Flexible solar film	Keep watching in the longer-term for development of more efficient, robust and cheaper systems; technology integration issues would require extensive consideration.	Foldable, portable solar panels (e.g. PowerFilm) are now in use by the US DoD in combination with the UBC. Further improvements include miniaturisation, greater efficiency with use of new coatings, and cost reduction for manufacturing. Further research is ongoing in perovskite cells, polymer solar cells, and the use of nanomaterials. [90-109]	Opportunity for leveraging off systems developed and tested by allied nations.
Energy scavenging technologies	Keep watching in the medium to longer term for maturation of these technologies to the point where they provide a viable solution for powering personal electronic devices, e.g. when they are able to offset some or all of the battery-carrying requirements of dismounted soldiers, in conjunction with advances in either battery or supercapacitor technologies.	Most of the designs remain in low to mid-TRL, although several systems are nearing production. Kinetic Energy Harvester leg-mounted exoskeleton will be tested by US DoD in 2017. New designs exploit small changes in humidity, pressure and temperature with use of novel materials. [76-89]	Close watch is recommended for the systems that are now tested for military use to assess their value proposition and key risks. Medium to longer term watch recommendation remains for less mature systems.
Soldier power integration and management	Conduct a holistic assessment of expected soldier power requirements for electronics to determine if this technology is needed in the near term. Australian and US systems can be trialled on a small scale to ascertain usability and integration requirements.	N/A	N/A
Transportation Technologies			
Autonomy kits for semi-	This technology has reached a sufficient level of maturity for serious investigation and	Bilateral trials are now taking place between Australia and the US to test autonomy kits for military vehicles.	Consideration of the concepts of employment for autonomy kits

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
autonomous convoys	trial. Partnering with international Defence organisations, industry and academia is recommended for in-depth examination of the ramifications of introducing this technology.	The TerraMax conversion kit for a range of tactical vehicles has been demonstrated by the US Marine Corps. [133-138]	will form part of the future human-in-the-loop simulation study to be run by DST Group in 2017.
All electric vehicles and electric power-trains	All-electric vehicles are not yet developed to practical usable stage for military applications. Electric powertrains for trucks coupled with range-extending generators are, however, a fairly mature and promising technology that can deliver substantial savings in fuel use and maintenance requirements. A cost-benefit analysis is recommended, with consideration of technology integration requirements and associated process changes.	Further developments in battery designs (as above).	Keep close watch on development of models with longer range, faster charge and improved battery life.
Insulating systems for transportation	Trial several systems to establish which ones offer the greatest functionality range and volume savings while still maintaining required temperatures for a range of products.	N/A	N/A
Amphibious ship-to-shore connectors	Separate analysis of options is recommended.	N/A	N/A
Autonomous and Robotic Systems			
Autonomous load-carriers for dismounted troops	Close watch is recommended as the concept is developed to a more practical level.	A lot of the programmes involved with the legged systems have now been divested. The wheeled versions have fared better with REX and SMSS systems now used in military contexts. [194-200]	Assess wheeled versions for potential expansion of distribution options for dispersed operations in contested areas.
UGVs for unmanned land mine and IED detection	Close watch is recommended as the concept is developed to a more practical level.	Small UGS are extensively used for mine/IED detection and clearance on military operations. [189, 190]	Opportunity for leveraging allies' experience in the use of such systems on operations.
UAVs for last-mile logistics	This technology may increase the cost of logistic operations but provide extended	Drone-based deliveries are being trialled by a number of large distributors. Medium-sized fixed wing UAS	Detailed studies are recommended for development

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
	reach, responsiveness and flexibility for distribution and evacuation tasks, without exposure of soldiers to more dangerous environments. Small drone delivery systems can be trialled for distribution of critical materiel to explore their functionality and limitations. Large multi-functional systems are expensive and require cost-benefit and detailed impact analysis.	(Shadow, Snowgoose) have been demonstrated for delivery of critical supplies in military settings. [10, 164-167, 170, 171]	of specific concepts of employment, risk-assessment and development of prototypes.
Exoskeletons	Keep close watch on this technology, especially as the US DoD begins trialling prototype systems and introducing them into service.	Exoskeletons are becoming more widespread with medical and industrial applications. US DoD TALOS programme remains on track for delivery in 2018 for use in special operations. It features ballistic protection armour, hybrid power supply, in-built cooling, low-light and thermal imaging sensors, and load-carrying augmentation. A light, non-powered system, (the Operational Exoskeleton, formerly Flexoskeleton) is being developed by DST Group. [209-214]	Keep track of operational use of this technology. DST Group prototype is undergoing testing.
Swarming	Disruptive technology. Separate impact analysis is recommended for examination of possible transformative effects for military operations and implications for land logistics.	Most military forces are now working on different types of counter-UAS systems. UAS swarming technology is being developed for military applications at DARPA and US ONR with recent demonstrations of the LOCUST programme and the 'Gremlins'. [181-188]	Incorporate UAS and swarm-based threats into red-teaming. Develop options for concepts of operations that allow for mitigation of this threat.
Materials and Manufacturing			
Additive manufacturing for parts replacement and repair	Partnering with industry and academia is recommended to explore the range of applications and issues associated with this technology. Maintaining expertise in this area would facilitate pilot trials of the more promising systems. Legal advice should be sought on issues of certification and IP rights.	3D printing of aircraft parts is now widely accepted within the aviation industry, whereas prototyping and repairs with the use of AM is becoming widespread across most industries. US DoD is investigating several approaches to the use of this technology on operations from rapid prototyping to 'instant' fabrication. New approaches are being developed to speed up production, combine different materials and embed electronics. [2, 215-228]	Develop metrics for assessing cost-effectiveness of AM for producing specific parts and use it to identify the most promising areas of application. Develop specific concepts of employment and assess their value proposition for the ADF.
Water production technology	Trial AquaSciences Emergency Water Station (EWS) and Dean Kamen's Slingshot systems on field exercises to establish their suitability for medium-to-large scale production of	Water generation units are now widely adopted by various military forces. An example is the GEN40V atmospheric generators and Water Treatment Units used within armoured vehicles by the Israeli Defence	Opportunity for leveraging of allies' experience in the use of such systems on operations.

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
	potable water at deployed military bases and in HADR settings.	Force and the French forces. New technologies include portable desalination units. [10, 253-255]	
Sensors			
'Internet of Things'	Close watch is recommended to identify mature, commercially available systems enabled by sensors that can extend logistic functionality for military systems.	IoT concept is now being adopted in design of ports and cities, although cyber security concerns are continuously highlighted for this type of connectivity. [256, 257]	Value proposition for sensor-enabled systems needs to be assessed in the context of potential system vulnerability.
Software tools for CBM	This technology is widely used in the aircraft industry and should be considered for adoption by the ADF, particularly in the Land domain. Trials of specific applications are recommended.	Development of novel, networked sensors in applications such as quality control [271].	Health and usage monitoring systems (HUMS) are already available in new military vehicles. However, their effective use requires upfront development of a long-term data management and exploitation strategy through relevant agencies.
Hand-held infrared spectroscopy	Close watch is recommended to identify potential diagnostic applications in deployed settings.	N/A	N/A
Low-cost sensors for inventory management	Process modelling of ADF logistic processes is required to assist in identification of the more suitable commercial systems. Small-scale trials are recommended due to the complexity of the total system with multiple operators and components interacting over time.	As per IoT (above)	As per IoT (above)
Information and Communication Technologies			
Vehicle to Vehicle (V2V) communication	This technology is on track to become ubiquitously available in commercial vehicles and a compulsory add-on in some instances. As such, it is likely to become a standard feature of military vehicles as well, as part of fleet upgrades.	N/A	N/A
Logistic Information Systems	Continue to monitor advances in LIS technology, noting that replacement of e.g. MILIS would require significant justification.	LIS upgrades and modifications are taking place across most allied forces, with the ADF looking to switch to a SAP-based system as well. The US Logistics	Experience of other nations indicates that key issues with effective adoption lay in the

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
	Continue a close watch on advances in ancillary technologies that support the LIS, including consideration of small-scale trials of selected tracking and real-time service technologies to support anticipatory logistics.	Modernisation Programme highlights this as a long-term process that works best with phased roll-out.	development of effective data management and data exploitation strategies, as well as careful consideration of roll-out and integration issues.
Localisation and local intelligence	Close watch is recommended as technology matures, with the view of identifying applications in asset tracking for logistic operations. Data management and security aspects require very careful consideration.	N/A	N/A
Augmented reality for logistic applications	Close watch is recommended as this type of technology gains traction in the commercial sector, with an increasing breadth and depth of products coming to the market. A potential technology with which to gain familiarisation and to explore in more detail the potential application areas beyond warehousing and stock inventory, such as tele-maintenance and telemedicine, in the military context.	Virtual reality headsets are now available to consumers. However, mixed reality (MR) systems such as Microsoft HoloLens and Vizux may be of more use for warehouse operations and tele-assistance. A number of new military platforms now incorporate augmented reality bullet-resistant windshields and VR instrument panels to replace glass windows. [10, 300, 301]	Opportunity for leveraging of allies' experience in use of VR/MR panels within military platforms. Mixed reality systems can assist in development of tele-assistance concepts of employment in maintenance and health.
Health Technologies			
Wound stasis systems	Collaborative trials with overseas partners are recommended once the systems are approved for human use.	Some new approaches for stemming uncontrolled blood-flow, although none yet trialled in humans. [309-312]	N/A
Blood substitutes	Close watch and collaborative trials with overseas partners are recommended once the systems are approved for human use. This technology can deliver substantial reductions in the logistic burden associated with provision of blood products to deployed units.	N/A	N/A
Telemedicine	Telemedicine applications can be trialled and used with existing ICT infrastructure for diagnosis in fields such as radiology, dermatology, parasitology and cardiology.	N/A	N/A
Portable	Keep close watch with view of purchasing	Portable systems are now available for detection of	An in-depth focused technology

Technology	Previous recommendations [2, 337]	Updates from horizon scan	Updated recommendation
diagnostic systems	and integrating into deployed health services functions when commercial systems become available, especially as their functionality increases. Particular systems of interest include paper-based diagnostics, digital stethoscopes, and microfluidic diagnostic devices, coupled to commonly available consumer electronics.	multiple pathogens and for genetic sequencing. Various medical devices have been re-designed to work as networked attachments to smartphones. Research continues on miniaturisation of sophisticated diagnostics such as MRI. [319-326]	scan is recommended to support development of specific concept of employment options.
Optical scan technology	Low TRL technology that still requires further studies and development to get to a practical stage for military operations; keep track and assess further if it becomes commercially available.	N/A	N/A
Wearable devices for health-state monitoring	Investigate further for suitability of real-time vital signs monitoring in situations where more sophisticated hospital equipment is not available (such as during evacuation via opportunistic platforms).	Popular and wide-spread type of consumer electronics, with some more sophisticated systems being used by elite sportsmen. New designs are emerging such as Biostamps. [327-330]	Look at developing specific concepts of employment (such as persistent soldier monitoring, casualty monitoring, training and fitness options); assess in the context of system vulnerability.

4.2 R-TAF Based Analysis for New Technologies

4.2.1 Airships

Technology description

Resurgence in airship technology has taken place recently, led by companies such as Aeroscraft and Hybrid Air Vehicles. The capacity of an exemplar fleet from Aeroscraft is shown below in Figure 13. Both companies offer working solutions for lighter-than-air travel with use of helium and both claim new ground-breaking capabilities for large-scale logistics. The airships can land on a range of terrains including water, as well as hover for several hours for loading and unloading.

spectrum.iee.org

Is the new technology useful to CSS?

A potential use within military logistics is the large-scale transportation of materiel, infrastructure and troops. The VTOL capability makes them useful in HADR or non-combatant evacuation operations (NEO) in areas with damaged airfield infrastructure. The manufacturers propose additional use as a ship-to-shore connector, such as in amphibious operations. Their size and payload capacity allows for the possibility of 'drop-in-place' prefabricated buildings and infrastructure such as medical facilities. They may also be used for 'air-basing' and as an aerial platform for providing wireless networking and C4ISR[24] capabilities.

Is the new technology better than the current solution?

This transportation method offers increased air lift capacity that exceeds anything provided by current fixed and rotary wing assets. It may extend the distribution range, as well as provide more Point-of-Entry (POE) options for a range of operations (e.g. amphibious). They offer an additional transportation option, making CSS more robust against degraded transport networks.

Conversely, an airship is significantly slower and has a lower ceiling than fixed wing assets. Its payload capacity can be easily matched by ground-based logistic convoys and is much smaller than maritime-based resupply vessel capacity. It also presents a very large, expensive, hard-to-miss target with a potentially significant payload. Operation under extreme weather conditions is yet to be tested. In the longer term, helium availability may present an issue as it is a limited resource. As such, this technology may offer the most benefit in providing additional distribution options, rather than replacing one form of cargo delivery with another.

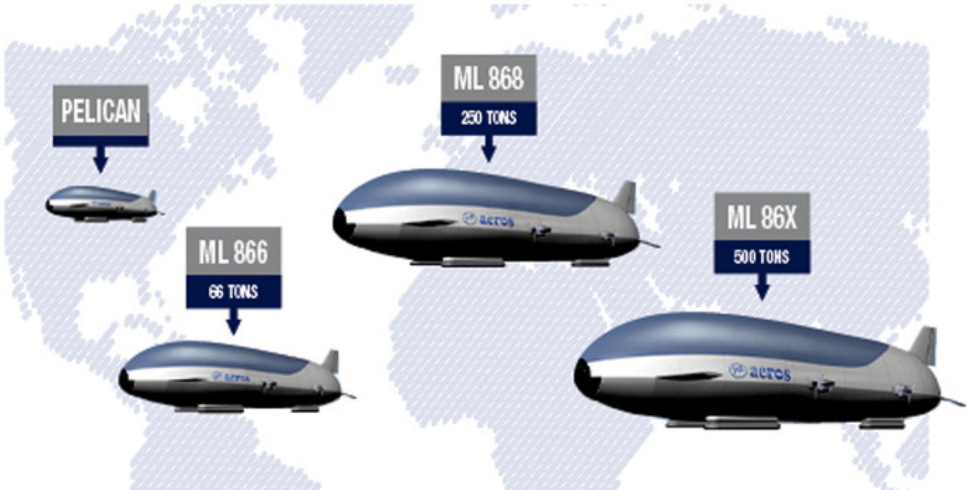
What is the cost involved?

The technology is at TRL 6-7, with some models already demonstrated in controlled trials. Some risk is involved in trialling them for military operations. Acquisition costs are likely to be comparable to those of a heavy lift cargo plane. These costs may be mitigated by adopting the 'as-a-service' model. Global helium prices are likely to impact operational costs in the long run. Ongoing running costs and maintenance liability is not known at this stage.

Sources of information

Airships have featured prominently in various news reports recently due to test flights with varying degrees of success [339]. This follows developments reported in S&T websites over a number of years [340-342]. Some technical information is available on manufacturers' websites [145, 343], although they present a biased, overly optimistic assessment of future impacts.

[24] Command, Control, Communications, Computer, Intelligence, Surveillance, and Reconnaissance



	PELICAN	ML 866	ML 868	ML 86X
PAYLOAD	0 Tons	66 Tons	250 Tons	500 Tons
LENGTH	266 ft	555 ft	770 ft	920 ft
WINGSPAN	96 ft	177 ft	296 ft	355 ft
HEIGHT	51 ft	120 ft	183 ft	215 ft
MAX SPEED	60 knots	120 knots	120 knots	120 knots
CRUISE SPEED	40 knots	100 knots	100 knots	100 knots
RANGE	N/A	3,100 nm	5,100 nm	5,100 nm
ALTITUDE CEILING	9,800 ft	12,00 ft	12,00 ft	12,00 ft
CARGO DIMENSIONS	N/A	220 ft X 40 X 30	380 ft X 74 X 45	455 ft X 74 X 54

Figure 13 Technical characteristics on the existing and future Aeroscraft fleet of airships[25] [145]

[25] Pelican is already operational; ML866 and ML868 are being built; ML86X is a future proposed model.

4.2.2 On-demand Manufacturing of Pharmaceuticals

Technology description

A portable manufacturing system that can be reconfigured to produce a variety of pharmaceuticals on demand. The prototype developed by MIT researchers is 1 m (W) x 0.7 m (L) x 1.8 m (H). Chemical reactions take place in the first module, at up to 250 ^{0}C and pressures up to 17 atmospheres. The solution is refined in the second module, then dissolved or suspended in water. An ultrasound is used for quality control. By swapping different module components, the operator can reconfigure the system to produce different pharmaceuticals. The current prototype can make four compounds (diphenhydramine hydrochloride, lidocaine hydrochloride, diazepam and fluoxetine). It can produce hundreds to thousands of doses in a day, but only as suspensions or solutions.

sciencedaily.com

Is the new technology useful to CSS?

This technology may present an additional option for supply of pharmaceuticals. It offers the desired effects of reducing stockholding and resupply requirements, reducing dependence on limited transportation platforms, facilitating force self-sustainability and rapid surge capacity. It is multi-functional and adaptive as well as relatively small and portable. It is not yet ruggedized or easy to repair. Due to the additional impost of purchasing, maintaining and stocking this type of equipment, a business case can only initially be made for production of pharmaceuticals that have some combination of high cost, long-lead time, sporadic and/or low usage, short shelf-life, and stringent transportation conditions (such as strict cold chain requirements).

Is the new technology better than the current solution?

The main advantage is in improving the robustness of CSS via additional flexibility, surge capacity, and reduced reliance on transportation assets. Indirect impact can be expected on force protection through better availability of particular pharmaceuticals for treatment. It is largely compatible with current concepts of operation, but presents additional requirements for specialist support, operator training, maintenance and supply of reagents. A key point of vulnerability is in the limited number of currently producible pharmaceuticals and biomedical technical support requirements.

What is the cost involved?

The most significant cost at this stage is developing the technology to a practically usable level, with a larger and more appropriate mix of pharmaceuticals. Because of this, close watch and 'intelligent customer' approach is recommended once more advanced and more practical systems become commercialised. The acquisition cost post-maturation cannot be determined at this stage. Additional imposts are in operator training, procedural integration, specialist maintenance support, and cost of reagents and replacement parts. This is offset by reducing the cost of transporting, storing, and writing off (on expiry) those pharmaceuticals that can be manufactured by the system.

Sources of information

The information on the MIT prototype was obtained through the original publication in a peer-reviewed journal (Science) [344] and associated electronic article on an S&T website (ScienceDaily) [336]. The MIT researchers were previously sponsored by Novartis, and now by DARPA. As continuous flow manufacturing is a topic of interest for many pharmaceutical companies, it is reasonable to expect that other prototypes are also being developed without publishing the results for commercial reasons.

5. Potential Disruptors

As discussed in the Introduction, the approach to identifying potential disruptors within this study is based on a qualitative assessment as to the technology's likely impact on military concepts of operations and the organisational ability to adapt [3]. They are further distinguished as 'direct' disruptors that by their nature influence military operations, and 'indirect' disruptors that may have transformative effects within society as a whole.

A number of emerging developments enable globalisation of sophisticated technology. This, in turn, enables transition of key threats from state actors to non-state actors, increasing the terrorist threat and reducing the ease of detection. The trend analysis is summarised in Table 3.

Table 3 Summary of potentially disruptive technologies

Technology	Potentially disruptive effects	References
Direct disruptors: Technologies that are likely to have a direct disruptive effect on military operations		
Cyber warfare	• With greater connectivity, sensors, and technology-dependence there are more points of vulnerability • Cyber-attacks for disruption and industrial espionage are becoming an additional form of warfare that is already used as part of national influence 'toolkit' across the world; they are routinely used to influence business deals and directions • Large-scale cyber-attacks may precede or replace large-scale invasions as a way of incapacitating the state enterprise and putting pressure on the government to concede to demands • Increased likelihood of synchronised attacks on satellite and other communication infrastructure in the event of large-scale conflict, interfering with achievement of joint effects and situational awareness	[10, 345-347]
Swarms	• Applications in overwhelming platforms, infrastructure and soldiers forcing large expenditure of ammunition and resulting in loss of key capabilities • Currently no effective countermeasures beyond laser systems, which would not be sufficient for large swarms • Potential for obsolescence of large armoured platforms and requirement for significant changes in military concepts of operation • Potential for undetected incursion and attacks against key civilian infrastructure • Potential for significant shift towards cost-imposing strategies and numerous, expendable platforms (war of attrition)	[162, 181-188, 348, 349]
Human-machine teaming	• New mix of capabilities for own forces and adversaries, potentially with changing tactics and reduced soldier exposure • As autonomous systems increase in complexity, it will become more difficult for human operators to fully understand the boundaries of their behaviour and accurately predict under what conditions failures might occur or how likely they will be • Roboticized battlefield with armed autonomous systems may entail a greater risk and damage from engagement of inappropriate targets, simultaneous failures, or mass fratricide • Changes in support requirement mix • Easy access to the technology for state and non-state actors creating new, and more numerous terrorist and battlespace threats	[9, 12, 25, 153, 350-352]
Artificial	• Use in tactical scenarios (e.g. air battles) to outpace human operators	[11, 122, 277-

Technology	Potentially disruptive effects	References
Intelligence	• De-humanisation of the battlefield • Danger of 'flash wars' – unchecked acceleration of conflict that results in disastrous strategic consequences	281]
Genetic manipulation	• Enabler for creation of new bio-agents which present potential threats • Ease of manipulation increases access to non-state actors	[353, 354]
Indirect disruptors: Technologies that may disrupt social structures on a larger scale		
Advanced battery designs	• Enabler for other technologies and industries: renewable home storage, all-electric vehicles, long-range small unmanned systems, sensors within Internet of Things • Disruptor for displaced industries: existing energy providers, car manufacturers, transportation industries • Likely to transform some common-place economic models for pricing and distribution of power, car-ownership, delivery, and surveillance • Enabler for 'bigger' data in the long-term	[29-54, 338, 355-358]
Driverless vehicles	• Improved safety and traffic flow management • Disruption of car ownership and legal liability models with new markets and economic opportunities • Improved mobility for elderly and disabled with associated workforce and social impacts	[122, 125-131, 135, 138, 304, 349, 359, 360]
Quantum computing	• Dramatic increase in computing power enabling other technologies such as artificial intelligence • Disruption of established security protocols and conventions • New forms of communication	[10, 272-274]
Artificial Intelligence	• Use to support military operations, removing a large degree of control out of human hands • Unknown implications of 'self-aware' artificial intelligence, with very large range of possible consequences • Some predictions that once superhuman intelligence evolves, the pace of technological development will accelerate beyond even the currently rapid pace, with humankind now outside the equation	[11, 15, 122, 277-281]
Genetic manipulation techniques	• Significant disruption of evolutionary balancing systems for humans and other animals, e.g. introducing a rogue microbe into the environment, or by genetic manipulation of embryos. • New approaches to design and manufacturing	[353, 354]
3D printing	• Enables new designs, mass customisation and technology globalisation • Disruption of traditional design, supply and manufacturing practices • The full range of potential applications is not yet known, which means a high degree of uncertainty in assessing future impacts • Bio-printing organs can have profound social implications if certain sections of the population can dramatically increase their life-span	[10, 178, 215-225, 227-229, 361-364]
Human-machine blending	• Evolution of humans to a cyborg-like stage with cybernetic implants, advanced medical prosthetics, and artificial organs • Blurring of boundaries between human and machine • Social re-structuring	[10, 302, 303, 332, 333]

6. Discussion

The key limitation of conducting a horizon scanning study across a broad range of technologies is that it is difficult to capture all significant developments in each technology area. This is exacerbated by certain reporting biases that exist in the way discoveries and new technologies are reported, and by lack of reporting for commercial-in-confidence developments. In addition, there is inherent uncertainty associated with forming predictions about complex socio-technical systems and the long-term effects of new technologies. As such, the more robust approach to treating studies such as this one is to consider the broad trends and their implications, and conduct strategic planning across a range of possible future scenarios.

Factors such as financial constraints and the relatively small scale of ADF military operations compared to the commercial trends that are driving technology developments across the world mean that the 'intelligent customer' approach remains appropriate for exploitation of new technologies. This involves horizon scan activities, in-depth technology impact analysis, comparison of possible concepts of employment, and partnering with industry and academia to draw on relevant centres of expertise.

The term 'disruptive' is often treated as a characteristic that is inherent within the technology itself. However, the magnitude of disruption and whether it becomes a threat or an opportunity is very much a function of the organisation's ability to adapt to and exploit the change. Hence, internal organisational processes and characteristics are an essential part of any discussion of technology impacts.

For military operations, it is logical to expect more significant disruption to come from those technologies (such as unmanned systems, AI and swarming) that impact military operations directly and offer significant shifts in tactical advantage. In contrast, technologies that can be expected to be transformative on a global scale may filter through to processes within military organisations in a more gradual manner.

7. Conclusions and Recommendations

This report is the third in a series of annual horizon scan updates that focus on new technologies for the ADF CSS. A number of technologies of interest were highlighted in previous reports. Several of these are now being adopted by military forces in allied nations, which presents an opportunity to draw on the allied experience with use of these technologies on operations:

- Hybrid generators (such as the HEIT system)
- Portable flexible solar films (such as PowerFilm)
- Energy-scavenging soldier systems (such as the Kinetic Energy Harvester)
- Water generation technology (such as WaterGen systems for armoured vehicles)
- Use of mixed and virtual reality panels in vehicles
- Use of AM for rapid prototyping and repairs.

In addition, development of detailed concepts of employment is now relevant for technologies such as AM, use of unmanned systems in distribution, portable networked diagnostics, and health-state monitoring.

To add to the previous R-TAF assessment, this report presents analysis for two new technologies: airships and portable systems for manufacturing of pharmaceuticals. Airships present an additional option for large-scale distribution of materiel and infrastructure without a requirement for air-fields. However, protection requirements, extreme weather conditions and platform cost are likely to hinder their use in contested and degraded environments. On-demand manufacturing of pharmaceuticals is not yet practically useful for military operations. A close watch is recommended due to the potential for improving robustness and efficiency of Class 8 supply chains once the range of pharmaceuticals improves.

Emerging technologies and trends that are likely to have a direct disruptive effect on military operations include: large-scale cyber-attack and satellite warfare capabilities, swarms, use of unmanned systems on the battlefield, and use of artificial intelligence at tactical level. Other technologies are likely to be transformative on a global scale with effects on economic models and social structures. One of these is advanced battery designs – currently a constraint on the large-scale shift to dispersed renewable energy generation, Internet of Things, all-electric vehicles and smaller-size UAS. Driverless vehicles are likely to result in re-structuring of car-ownership models and open up new economic markets at the expense of some existing ones. Quantum computing is often predicted as the next disruptor in computing and communications. However, the more disruptive effect that may arise from any substantial improvement in computational power is the development of more sophisticated artificial intelligence systems. In the longer term, novel genetic manipulation techniques and neural interface technology may present new challenges to social conventions and structures.

Some broad recommendations for analysis of emerging technologies in the context of military operations include:

- Development of redundant/alternative C2 methods that allow operations under conditions of degraded communications
- Incorporation of detailed long-term data management, security and exploitation strategies within the acquisition process for any networked technologies
- Incorporation of unmanned systems, swarms, and wide-spread cyber- attacks against civilian and military systems in Red teaming exercises
- Development of technology concepts of employment that are robust across a range of operational environments, including more extreme events and those that involve breakdown of global supply chains for fuel
- Continuation of horizon scanning and impact analysis studies with 'deep dives' for identified areas of threat and opportunity
- Development of robust teaming concepts that draw on natural strengths of human and machine intelligence.

These recommendations are made in the context of an ongoing review of logistic concepts of operations, to allow for more dispersed, nodal operations that may take place within civilian settlements, and to allow for greater concurrency of support requirements.

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Appendix A Horizon Scan for Power and Energy Technologies

Examples	TRL	Applications and Benefits	Challenges and Barriers
Batteries			
Tesla, US; Redflow, AUS: The Tesla Powerwall is a home energy storage solution for storage of solar energy generated during the day: rechargeable lithium ion battery with liquid thermal control [53]. Similarly, Redflow's Z-Cell is based on flow battery technology for achieving the same purpose [54], which can be scaled up to industrial-sized applications.	TRL 8-9	Enabling a sustainable shift to use of solar for residential homes.	High initial investment cost and limited capacity; disruptive for current energy providers.
US DoD: Hybrid generators that use conventional fuel, solar panels and batteries have been incorporated into the Hybrid Energy ITV (Internally Transportable Vehicle) Trailer (HEIT) developed and demonstrated in 2014. It is intended to provide a Company Landing Team with a highly mobile, MV-22 Osprey transportable electric power solution that is matched to energy demands and works with various energy sources [338].	TRL 8-9	More efficient power generation and longer generator life.	Costs of retrofitting and system integration
Stanford University, US: Method for inhibiting the growth of lithium dendrites within lithium-ion batteries through adding two chemicals to the electrolyte in the battery. Dendrites can cause li-ion battery fires when they penetrate the two halves of the battery, creating short circuits and overheating [29].	TRL 6-7	Improve cyclic performance and slower degradation for current batteries. For future battery technology, this would overcome a significant barrier in the development of lithium-sulphur and lithium-air batteries, which can theoretically hold up to 10 times the energy density of lithium-ion batteries.	The technology is yet to be incorporated into extant batteries. The next step is testing whether the approach can prevent dendrite formation in larger-scale cells that closer to practical batteries.
Stanford University, US: Researchers have developed a li-ion battery that will shut down before overheating, and restart again when it cools. This is done through graphene-coated nickel particles ('spikes') embedded in a polymer. When cool, the spikes are in contact, and so they conduct electricity. When heated, the spikes physically lose contact with each other, and the battery stops [33].	TRL 4	Improved safety through a reduction in 'thermal runaway' events leading to fires. No performance degradation through repeated shutdown/restart cycles.	
MIT & 24M, US: Cost-effective, simpler process for producing a hybrid battery with semisolid colloidal particle suspension electrodes. Fewer, thicker electrodes mean less distinct layers, no drying stages in production, and 80% reduction in amount of non-	TRL 6	Light, small, flexible and resilient batteries that can be bent, folded, or penetrated by bullets without using functionality. Potential applications are	Mid TRL technology that is yet to be proven in practical applications.

functional structure material [34].		in grid-scale installations to help smooth out power loads and act as back-up for renewable energy sources with intermittent output. It is also well suited to applications where weight and volume are limited, such as in electric vehicles.	
UNIST[26], South Korea: Printable solid-state (PRISS) Li-ion batteries with a new manufacturing method that does not require either liquid electrolyte injection or separator membranes. The electrolyte is made of a paste, the electrodes are made of slurry, and are consecutively printed onto a surface and then cured with ultraviolet light [31].	TRL 6	The technique replaces pre-designated battery space with fixed dimension and shape with potential uses in wearable electronics and Internet of Things.	Further research is required to prolong battery life and increase energy density.
Binghamton University, US: Paper-based biologically-powered battery that creates power from microbial respiration, delivering enough energy to run a paper-based biosensor with a drop of bacteria-containing liquid [39].	TRL 6	Low cost, biodegradability; can potentially be paired with emerging paper-based sensing devices to provide a source of power which is useful when working in remote areas with limited resources.	Incorporation into actual devices is yet to be demonstrated.
University of Illinois, US: High-performance microbattery that can be integrated into microchips at production volumes. This is achieved through a combination of 3D holographic lithography and 2D photolithography to create the necessary microstructures [37].	TRL 5-6	Potential applications in miniaturised sensors such as MEMS sensors, implanted sensors, medical devices, actuators, and wireless transmitters.	Further work is required to improve battery life; currently does 200 cycles with 12% capacity fade.
University of Texas, US: A semi-liquid battery with liquid electrolyte, liquid cathode and solid lithium anode [32].	TRL 5-6	Energy density comparable to li-ion batteries; power density is comparable to supercapacitors; maintains performance at high rates of charge/discharge.	Work still needs to be done to improve the lithium anode. Long-term durability testing under operational conditions not yet undertaken.
University of Illinois, US: Device that uses miniaturised batteries and solar cells connected with wires within layers of rubber. The device is approximately 2.5 mm thick and can be recharged wirelessly [38].	TRL 5	Potential applications include use in health-state monitoring devices and to aid patients with muscular or neurological disorders.	The demonstration device has a lifetime of only a few hours, although this can be increased.
Friedrich-Schiller-Universitaet, Germany: A new type of redox-flow battery that uses organic polymers and a harmless saline solution in	TRL 5	Suitable for bulk storage of energy; useful as a buffer for sporadic energy	Yet to be commercialised.

[26] Ulsan National Institute of Science and Technology

place of the toxic chemicals previously used in redox-flow batteries (e.g. heavy metal vanadium dissolved in sulphuric acid) [41].		generation from renewable sources; non-toxic.	
National University of Singapore: A new chemistry for a redox-flow battery has been developed, using suspended granules of lithium-iron phosphate in the cathode tank, and suspended granules of titanium dioxide in the anode tank. Because the lithium is stored in solid form in granules, this gives about 10 times the capacity of a vanadium redox battery [42].	TRL 4-5	Higher capacity than vanadium flow batteries, without the toxic vanadium.	Charge/discharge rate is four orders of magnitude slower than for a vanadium flow battery. Improvements to membrane (or 10000 times more membrane) are needed to address this.
University of Maryland, US: Solid state battery made of just one material that can both move electricity and store it. The material is made of a mix of sulphur, germanium, phosphorous and lithium and has properties of both electrode and electrolyte. Carbon is added at each end to make the electrodes [40]. Additional advances in solid-state batteries: [355-358]	TRL 4-5	Simple to make and (in theory) should be able to work over large number of charge/discharge cycles. Other potential advantages of solid state batteries include higher thermal durability, increased energy and power density.	Proof of concept stage with testing of cyclic performance underway. Sulphurs degrade into poisonous gases and researchers are looking into alternative materials.
Pohang University, South Korea: Molecular nanostructure for lithium-ion batteries, based on pumpkin-shaped molecules organised into a honeycomb structure that enables lithium ions to diffuse more freely than in conventional batteries and exist without separators [30].	TRL 4-5	Improved battery performance and reduced risk of overheating that can lead to catastrophic ‘thermal runaway’.	Mid TRL technology that is yet to be proven in practical applications.
University of Wollongong, Australia: Three-dimensional structure for energy storage using a flat-pack self-assembly of three components: graphene, a conductive polymer and carbon nanotubes. The resulting wafer is highly conductive, lightweight, and can be folded like a roll or a stack. The researchers also claim that it can store and deliver charges at higher speeds and that it will be lighter than traditional batteries [35].	TRL 4	Improved energy storage for flexible, wearable technologies that can be cheaply and easily fabricated.	Scaling up is yet to be demonstrated. Actual batteries/supercapacitors haven't yet been produced from this material.
University of California, US: Nanowire-based battery material that can be recharged hundreds of thousands of times. Gold nanowires are coated in a manganese dioxide shell and encased the assembly in an electrolyte made of a Plexiglas-like gel [36].	TRL 4	Reliable, resistant system that can be cycled up to 200,000 without loss of functionality. Applications in computers, smartphones, appliances, cars, spacecraft, etc.; potentially significant reductions in the weight that soldiers have to carry and reduce associated resupply chains.	Low TRL technology.
Stanford University, US: Aluminium batteries with aluminium anode paired with a graphite cathode, and an ionic liquid electrolyte, all	TRL 4	7500 charge/discharge cycles without loss of capacity, is flexible, “ultrafast”	Current prototype produces about half the voltage of a lithium-ion battery.

inside a flexible polymer-coated pouch [43].		to charge, cheaper and safer than lithium-based batteries as it doesn't catch fire even when damaged [43].	Further development is required for this technology to become commercialised.
Australian Nuclear Science and Technology Organisation, Chinese Academy of Sciences: Sodium-ion battery technology is a promising alternative to the now almost-ubiquitous lithium-ion battery. Previously having been stalled by the need to improve energy density, cyclic life and better electrode materials, researchers have determined a new electrode material that avoids many of the problems of previous electrode materials [44].	TRL 3	Sodium is cheaper, non-toxic, and more abundant than lithium.	Still to overcome the slow charge and discharge rate problem, making them infeasible for high-power applications, and the energy density problem.
University of Illinois at Chicago, US: Researchers have demonstrated that they can replace a lithium ion, which carries a single positive charge, with a magnesium ion, which carries two positive charges, using electrodes similar in structure to those used in today's lithium-ion batteries (i.e. that magnesium ions can be reversibly inserted into electrode materials). This brings magnesium-ion batteries one step closer [45].	TRL 3	Doubles the electricity produced per ion exchange when compared to lithium-based batteries, hence the potential for higher energy densities.	Only one piece of a battery, bot a battery yet.
Case Western Reserve University, University of North Texas: A new carbon-foam-based catalyst for rechargeable zinc-air batteries has been created, that performs as well or better than most previously reported catalysts, including platinum/metal oxide-based ones. The new carbon nanostructure works efficiently for both the oxygen reduction reaction (ORR) and the oxygen evolution reaction (OER) – two key chemical reactions in metal-air batteries [46].	TRL 4	Cheap, easy to make and environmentally friendly. Has the potential to replace expensive platinum and other metal-based ORR and OER catalysts in a wide range of applications, including fuel cells, metal-air batteries, solar cells and even water-splitting systems.	
Argonne National Laboratory, U.S. Department of Energy: Researchers have found a way to produce lithium superoxide instead of lithium peroxide during Lithium-air battery discharge [47].	TRL 3-4	Lithium superoxide easily dissociates into lithium and oxygen, leading to good cycle life and high efficiency. It also opens the way for a lithium-air battery built in a 'closed system' that doesn't require intake of extra oxygen from the atmosphere.	
University of Cambridge: A refinement of lithium-air batteries has been developed, using lithium-iodide and a water-based electrolyte, that avoids the gradual build-up of lithium peroxide that plagues conventional designs [48].	TRL 4-5	90% more efficient than lithium-ion batteries, and capable of over 2000 cycles (compared to lithium-ion's several hundred).	Problems still remain to be solved before this chemistry becomes commercially viable.

EMPA and ETH Zurich, Switzerland: a sodium-magnesium hybrid battery has been developed, comprising iron, sulphur, magnesium and sodium, all abundantly available and inexpensive materials. It has been dubbed the 'Fools Gold' battery because of the use of pyrite (crystallised iron sulphide) [49].	TRL 4-5	Safe, durable, affordable. Is targeted toward large-scale energy storage such as that required to decouple renewable sources from consumers.	40 cycles without degradation in performance, but much more testing is required. Not suitable for electric vehicles due to low energy density.
Georgia Institute of Technology, US: Work is being undertaken on overcoming the mechanical limitations of silicon for battery electrodes. Primarily their brittleness and inability to cope with significant volume changes (up to 280%) during charging and discharging, resulting in cracking [50]. Other advances in the use of silicon for electrode materials include [51, 52].	TRL 3-4	They have the potential to store up to 10 times as many lithium ions than conventional graphite electrodes, hence the potential to offer substantial energy density improvements over current lithium-ion batteries.	The claim of "surprisingly high" damage tolerance may not necessarily be high enough for military applications. Requires battery charge levels to be kept high enough for the silicon to remain in a ductile state.
Supercapacitors			
University of Delaware, US: Carbon nanotubes were used to improve the energy density of dielectric capacitors. Using 3D nanoscale 'interdigital electrodes' allowed researchers to reduce the distance between the opposing electrodes and increase the surface area of each electrode, and hence the electrostatic potential to store energy has increased [55].	TRL 5-6		It is unclear how this compares to current and emerging supercapacitors in terms of cost, energy or power density.
UC Santa Cruz, Lawrence Livermore National Laboratory, US: 3D printed graphene electrodes for supercapacitors have been produced that outperform comparable electrodes made via traditional methods, and 'nearly' retain their energy capacity after 10,000 cycles [56].	TRL 4	The usual advantages of supercapacitors, manufactured with a much cheaper process than other types of electrodes.	Improvements sought by the researchers include new 3D designs, different inks, and improving the performance of existing materials.
A*STAR Singapore Institute of Manufacturing Technology; Nanyang Technological University and Jinan University, China: So-called asymmetric supercapacitors have been created by researchers, using different materials for anode and cathode. This is unlike traditional supercapacitors, which use the same material for both. It also uses a solid state electrolyte that prevents corrosion of the electrodes [58].	TRL 3-4	High capacitance and high power density have been reported.	Although 'high power density' was reported, it wasn't quantified in the article.
Drexel University, US & US Naval Academy: Flexible supercapacitors based on activated carbon particles embedded into different types of yarn to form a knitted textile that can store energy to power sensors and electronics integrated into smart clothing [59].	TRL 5-6	Manufactured without involving expensive materials (e.g. activated carbon instead of carbon nanotubes), hence cheaper and non-toxic.	Yet to be commercialised
City University of Hong Kong, China: A yarn-based supercapacitor that can heal itself both mechanically and electrically [60].	TRL 4-5	As a yarn, can be woven into fabrics like clothes, for harvesting/scavenging energy and powering sensors.	Usual problems with capacitors - energy density. It is unclear how well the capacitor performs after damage and self-healing vs. before, or how its performance degrades over multiple

			break/self-heal events.
MIT, US & University of British Columbia, Canada: New approach using yarns made from niobium nanowires as the electrodes in micro-supercapacitors. It can store and release electrical power in bursts. This is useful for small devices due to greater efficiency compared to fuel cells, batteries, and flywheels which are too complex to be practical when reduced to very small sizes [61].	TRL 4	Particularly applicable to small low-power sensors and other small devices that transmit periodically. The niobium yarns are stronger and 100 times more conductive than equivalent supercapacitor yarns made using carbon nanotubes. The researchers claim to have "fairly high volumetric power density, medium energy density, and a low cost".	So far, the material has been produced only in lab-scale devices. The next step, already under way, is to figure out how to design a practical, easily manufactured version.
Linköping University, Sweden: Paper-based capacitors – so-called "Power paper" – have been developed by researchers, built from nanocellulose and a conductive polymer. It has set records for the highest charge and capacitance in organic electronics, amongst others. Energy density is similar to supercapacitors [62].	TRL 4	Made from simple materials - cellulose and an easily available polymer. Flexible and light in weight, no dangerous chemicals or heavy metals, can be recharged hundreds of times, recharges in seconds, and is waterproof.	Hard to see a downside, if they can be developed to be produced on an industrial scale.
University of California at Los Angeles, US: A 'foundry-realisable' technique for integrating small supercapacitors directly on silicon wafers has been developed. Previously this was problematic [63].	TRL 4	Opens up the ability to fabricate microelectronics with inbuilt supercapacitor energy storage, useful for small sensors, embedded computing, memory backup and the like.	
Rice University, US: Researchers have produced flexible, solid state micro-supercapacitors using laser-induced graphene. They are made by burning electrode patterns with a commercial laser into plastic sheets at room temperature [64].	TRL 3-4	These rival the best supercapacitors available for energy storage and delivery. Cheap and fast to produce (room temperature, no complex fabrication conditions).	Industrial-scale manufacturing processes still to be developed.
Gwangju Institute of Science and Technology, South Korea: Significant gains in performance of supercapacitors [57, 365] with a new, non-toxic, low-temperature process for creating graphene with better electrochemical properties. The claim is an energy density of 131 Watt-hours per kilogram (Wh/Kg), nearly four times the previous record for graphene-based supercapacitors (35 Wh/Kg) and approaching the 200 Wh/Kg for an average li-ion battery [366].	TRL 3	Lighter, and eventually cheaper, alternatives to electrochemical battery technology; although still inferior to li-ion for capacity, the speed of charge is a much more significant advantage - moments (seconds) instead of hours.	Not there yet in terms of energy density to be a viable replacement for e.g. li-ion batteries.

Fuel Cells			
Bristol Robotics Laboratory, UK: Microbial fuel cells (MFC) that allow continuous operation without refuelling. The scientists have created Row-Bot: a robot that floats on water. It takes in 'dirty' water, generates electricity to power its forward motion via paddles, then ejects slightly cleaner water before taking on more dirty water. There is also energy to spare for powering, e.g. small sensors. It can swim for as long as it has suitable water to float around in [75].	TRL 6	Potentially useful for environmental monitoring, and/or powering small sensor networks. May be able to take advantage of e.g. "grey" or even "brown" waste water while units are operationally deployed, with the added bonus of cleaning the water slightly.	Current design is mostly a test-bed to integrate MFCs with actuators. Lots of optimisation still required.
Pohang University of Science and Technology, South Korea: Miniature Solid Oxide Fuel Cell (SOFC) that provides enough energy to keep a small UAS flying for over an hour. The researchers used porous stainless steel in combination with thin-film electrolyte, brought together using tape casting-lamination-cofiring. Together with low heat capacity electrodes, this amalgamation results in increased performance and better long-term durability. The system showed peak power density of 560 mW per cubic cm at 550^{0}C [70].	TRL 4-5	Apart from powering UAS, it may also have applications in smartphones, cars and other items. The researchers claim that the Postech device has fast on and off times similar to lithium-ion batteries and superior power densities, which would allow it replace lithium batteries in mobile electronics.	Yet to be scaled up and commercialised.
University of South Carolina, US: Substantial improvement in the electrical conductivity of a material commonly used as an electrolyte in solid-oxide fuel cells [68].	TRL 5	Improved conductivity in the electrolyte of a solid-oxide fuel cell means a faster and more efficient conversion process, meaning more electrical energy can be created from the same amount of fuel.	Enabling technology (not a complete fuel cell design)
Department of Energy, US: A new metal oxide has been discovered whose atomic structure includes highly ordered arrays of missing oxygen atoms. This structure allows oxygen ions to move through the material quickly and easily at low temperatures – very important for solid oxide fuel cells [69].	TRL 5	The material discovered in this research enables more efficient solid oxide fuel cells, and to operate at much lower temperatures than current technology.	A component of a fuel cell, no working prototypes incorporating this component as yet.
Chongqing University, China: New non-platinum, non-precious metal catalyst with high number of 'active sites' for use in proton-exchange membrane fuel cells [71].	TRL 4	Any improvements to fuel cell performance or cost is of profound potential benefit.	
Northwestern University, US: Researchers have discovered that thin clay sheets, when exfoliated in water and dried into paper-like films and assembled, produce proton nanochannel structures suitable for proton-exchange-membrane fuel cells [72].	TRL 4	Much cheaper than current mechanisms used to produce nanochannels, using more benign chemicals (water) for exfoliation, and high thermal stability.	No indication of area of application other than the implication that it may be able to be used where existing proton exchange membranes are used, such as in fuel cells. No indications of the effectiveness of this new material vs. existing equivalent materials.

Horizon Unmanned Systems (HUS), Singapore: The first hydrogen fuel cell powered multi-rotor UAS, HYCOPTER. The special fuel cell was designed by Horizon Energy Systems (HES), which recently announced a new 700Wh/kg solid hydrogen storage system. HYCOPTER makes use of its frame structure to store the energy in the form of hydrogen [73].	TRL 5-6	The fuel cell technology extends the UAS flight endurance to four hours, which is 8-10 times longer than the average flight duration of equivalent systems to date. Furthermore, HYCOPTER design effectively stores equivalent energy of 3 kg of lithium batteries as 120 g of hydrogen, which reduces lift power requirements [73].	Hydrogen fuel is associated with specific risks as hydrogen is highly flammable and ignites more easily than other fuels. It is also colourless and odourless, making it difficult to detect.
Intelligent Energy: DJI Matrice 100 quadcopter powered by a hydrogen fuel cell that weighs 3.5 pounds (lighter than the battery it replaces). Boeing and others have their own fuel-cell drones [74].	TRL 7	Hydrogen fuel cells are likely to extend UAS flight endurance and range.	Hydrogen fuel is associated with specific risks as hydrogen is highly flammable and ignites more easily than other fuels. It is also colourless and odourless, making it difficult to detect.
Energy scavenging			
Bionic Power Inc.: The company has received a US$1.25 million contract from the US Office of the Secretary of Defense to supply low-volume production units of the PowerWalk® Kinetic Energy Harvester. The units will undergo field trials under the Joint Infantry Company Prototype (JIC-P) Program. It is a light-weight, leg-mounted exoskeleton designed to allow for full range of motion and harvest energy from walking. It also reduces muscle fatigue during downhill walking [76].	TRL 6	PowerWalk harvesters reduce battery weight that soldiers have to carry while providing continuous power for communications, navigation and optic devices.	Yet to undergo field testing in relevant environment
US Army Research Laboratory: An Energy Harvesting Backpack is being developed, based on harvesting the motion of the backpack bouncing up and down as a soldier walks or runs [77].	TRL 6	An alternative energy source to supplement that carried by soldiers, potentially reducing the number of batteries required.	Some trials suggest participants feel the motion of the backpack makes them feel off-balance. (Others thought it felt more comfortable than the existing assault packs.)
University of Wisconsin-Madison, US: Reverse electrowetting is particularly good for converting the small mechanical displacements and large forces of footfalls, when combined with a new 'bubbler' technique [78].	TRL 7	Likely to be commercially viable. 10 watts/m^2 has been achieved, with theoretical estimates showing 10kW per square metre may be possible.	
Eindhoven University of Technology, Netherlands: Use of evaporation to power small devices by exploiting changes in the size of bacterial spores (about 6%) with changes in humidity. When thin layers of spores are glued on a curved polymer sheet, the change	TRL 4	Trials indicate that the strips, when shrinking, can lift more than 50 times their own weight (although slowly) [79].	The power generated is quite low due to slow movement. Low maturity technology.

causes it to stretch and contract. Stringing together series of sheets creates 'artificial muscles' that quadruple in length when humidity changes from less than 30% to more than 80%. Use of the 'muscles' in a Ferris wheel-like device was enough to power a 100g toy car [79].			
Columbia University, US: Two new devices that derive power from evaporation: a floating, piston-driven engine that generates electricity, and a rotary engine. The team's 'Moisture Mill' contains a plastic wheel with protruding tabs of tape covered on one side with spores. Half of the wheel sits in dry air, causing the tabs to curve, and the other half sits in a humid environment where they straighten. As a result, the wheel continues to rotate, acting as a small engine [367].	TRL 3-4	The researchers built a small toy car that is powered by the rotary engine to demonstrate the principle.	Low maturity technology
University of Maryland, US: Nanopaper-based generator that converts mechanical energy into electrical power. The researchers developed a transparent-paper device that can generate electrical power from a user's touch by exploiting electrostatic induction. Pressing a 2x2 cm generator produces enough current to light up a small liquid-crystal display [81].	TRL 4	The paper energy harvester could be used to make disposable, self-powered touch screens that fold, interactive light-up books, touch-sensitive skin for prosthetics, and security systems for art and documents. The device is robust and continues to produce a steady current for more than 54,000 press-release cycles. It is attractive for mass production and eventual environmentally-friendly disposal.	Low maturity technology
MIT, US & Taiwan Semiconductor Manufacturing Company, China: Nanogenerator for harvesting energy from rolling tyres. It relies on the triboelectric effect to harness energy from the changing electric potential between the pavement and a vehicle's wheels. The nanogenerator relies on an electrode integrated into a segment of the tyre [368].	TRL 5	The friction between the tire and the ground consumes about 10 percent of a vehicle's fuel. If it can be converted to energy it is an improvement in fuel efficiency.	Despite the claims of the researchers of reducing fuel consumption by 10% given a 50% recapturing of the energy lost to friction, this doesn't actually seem to be capturing the energy lost to friction (the majority of which ends up as heat). It is more likely to be a type of parasitic energy scavenging/harvesting, but unlikely to scavenge anything close to the 10% of energy lost to friction.
MIT, US: A new power converter chip that can harvest more than 80 percent of the energy trickling into it. It can charge a battery and directly power a device. All of those operations also share a single inductor—the chip's main electrical component—which saves on	TRL 6	This solution provides a significant improvement over existing solutions for power conversion in extremely low power applications - 80% efficiency up	Yet to be commercialised.

circuit board space but increases the circuit complexity even further. Nonetheless, the chip's power consumption remains low [369].		from 40-50%. A key enabler for the internet-of-things concept, and distributed sensor networks that do not require an external power source (can generate/scavenge/harvest their own).	
Georgia Institute of Technology, US: Microphone that harvests sound energy through a triboelectric effect. The device is made of paper the size of a postage stamp, with minuscule holes burned in it using a laser, and one side coated with copper and the other with Teflon [82].	TRL 4-5	Potential application in powering small sensors, trickle-charging or extending the life of existing batteries.	Only 121 milliwatts per square metre has been reported. Improvements in efficiency are required for practical use.
Various, South Korea; California Institute of Technology, US: Researchers have developed a scalable manufacturing method for a state-of-the-art alloy used in creating thermoelectric devices. This technique also improves the thermoelectric conversion efficiency of the material, doubling the industry standard [83].	TRL 4-5	Significant implications for harvesting waste heat as electricity, localised power production for small sensor devices, and for more efficient cooling when a traditional compressor arrangement is not appropriate or feasible.	Unclear from the article if they are approaching the efficiency of e.g. refrigerated cooling devices – more investigation needed.
Northwestern University, US: The most efficient thermoelectric material to date has been produced by doping tin selenide (previous record holder) with sodium. This gives a much broader range of temperatures for which the material is effective when compared to tin selenide, exceeding that achieved in the above article [84].	TRL 3	As above.	
University of Manchester, UK: More advances in thermoelectricity production: searching for suitable materials and finding nanostructures that work well. The desire is to find materials that are cheaper and less toxic than current materials [85].	TRL 3-4		Discoveries thus far are still much less efficient than commercial materials.
MIT, US: Quantum dots are being investigated for their potential to generate electricity from heat. A quantum dot 'rectifier' has been created, which converts alternating current to direct current, and has been shown in principle to be able to harvest electrical energy from waste heat through tiny fluctuations of voltage and current [86].	TRL 3-4	Another energy-scavenging technique for waste heat, this time targeting electronics, and at the nano-scale – much smaller than would normally be associated with e.g. Peltier devices	Low maturity technology, in the range of picowatts for this single device. Practical application will depend on ability to scale it up.
University of Colorado, US: Production of thermoelectricity through the use of 'rectennas' (combining functions of antenna and rectifier) that capture thermal radiation. These are good at capturing the lower end of the thermal radiation spectrum, but not the higher end (which is where a lot of waste heat from hot objects is expended). Scientists	TRL 3-4	Another energy-scavenging technique for production of thermoelectricity.	These types of nanoscale surface topologies, or the use of rectennas, may not be appropriate in all situations. No quantification is given as to the likely improvements to be expected, or how it

have produced a nanoscale surface topology, 'spectrally tuned', that enhances the amount of low-energy thermal radiation emitted, making harvesting using rectennas more effective [87].			compares to other techniques for harvesting thermal energy. Low maturity technology.
Ohio State University, US: Technology to capture some of the wasted EM radiation from mobile phones and extend single battery charge by 30% [88].	TRL 6-7	Can be built into a mobile phone case. Because the harvesting is so close to the source, significant power can be scavenged – much more than those that harvest ambient RF energy from the environment.	The balancing act is to make sure that device performance is not degraded. The device only works when the phone is transmitting.
Drayson Technologies & Imperial College London: 'Freevolt' technology comprising a multi-band antenna and rectifier to harvest ambient RF energy, including from mobile phones [89].	TRL 7	May help extend the battery life of portable electronic devices.	Only small amounts of energy can be harvested this way and the energy generated will fluctuate.
Solar photovoltaics			
PowerFilm: PowerFilm has been awarded a contract to build solar panels in support of the Thales $49M Universal Battery Charger (UBC). The company's advanced lightweight 120 watt foldable solar panel was chosen as a primary accessory to the UBC [90].	TRL 8	The system is to be used in remote areas to charge multiple battery types. It is lightweight, foldable, durable and portable, fitting into a rucksack. It will supply power to the UBC allowing the squad or platoon to operate for at least 72 hours without battery resupply [90].	Extra weight for soldiers to carry, but offset by reduced battery requirements
MIT, US: Demonstration of very thin, very light solar cells that may help power portable electronic devices. This is achieved by making the solar cell, the substrate and a protective coating all in one process (using established vapour deposition techniques). In the proof-of-concept experiment, the researchers used a common flexible polymer parylene as both the substrate and the overcoating, and organic material DBP as the primary light-absorbing layer [91].	TRL 4	The manufacturing process takes place in a vacuum chamber at room temperature and without use of solvents (unlike conventional solar-cell manufacturing). The benign manufacturing condition mean that the substrate and solar cell can be deposited directly on fabric or paper, or other fragile materials [91].	Low TRL – proof-of-concept only.
American Chemical Society, US: Researchers developed a glass coating that helps underlying solar cells harvest sunlight from multiple angles. The coating also self-cleans [92].	TRL 5-6	Conversion efficiency increases by over 5% to 27.7% due to capture of more ambient light. The amount of energy generated throughout the day by a cell that cannot track the motion of the sun increases by up to 46 percent. Loss of performance due to dirt is also reduced.	

University of California, US: Hybrid material that first captures two infrared photons that would normally pass right through a solar cell without being converted to electricity, then adds their energies together to make one higher energy photon. Essentially, this material is reshaping the solar spectrum to better suit the capabilities of existing solar cells [93].	TRL 4	Claims by the authors of a 30% increase in efficiency of conventional solar cells. More efficient solar cells means less cells are required to generate the same amount of power, or more power can be generated from the same number of cells.	No mention if this could be a coating to be applied ('retrofitted') to existing solar cells already produced, or whether this would be an integral part of the production process for new cells.
Florida State University, US: Parallel research is being undertaken on upconverting two low energy green photons into a single higher energy blue photon, through mechanisms integrated into the cell itself, rather than as an upconversion filter applied to the cell [94].	TRL 4	Up to 45% conversion efficiency from 33%.	How scalable or expensive the process is, is not quantified.
University of New South Wales, Australia: Solar cell device with 35% efficiency, breaking the previous world record of 24%. The solar cell configuration splits sunlight into four separate bands. Different parts of the cell with different layers absorb the different bands of sunlight with various materials optimised for maximum efficiency [95].	TRL 5	Another step in improving efficiency of photovoltaics.	The multi-junction solar cells are expensive to manufacture, which would be a barrier to commercialisation.
Ecole Polytechnique Federale de Lausanne, Switzerland: Over 20% efficiency for perovskite based solar cells by briefly reducing pressure during crystal fabrication. This is the highest efficiency achieved for this type of cell so far and matches the performance of conventional thin-film solar cells of similar sizes [96]. In addition, a key material making up perovskite cells that that is both cheaper and more effective has been developed [98].	TRL 5	Perovskite technology is low cost and is already under industrial development.	Safety concerns remain over the lead content of current perovskite solar-cell prototypes. Stability of the devices also needs to be improved.
National Institute for Material Science, Japan: More stable perovskite solar cells have been produced through simplifying their structure [99].	TRL 5	Overcomes the common challenges for perovskite cells of not being sufficiently stable or reproducible for commercial applications.	Yet to be commercialised.
Institute of Chemical Technology, South Korea: A more efficient technique for the manufacturing of perovskite solar cells, which also allows for the cells to capture a broader spectrum of light [97].	TRL 5	Cheaper, more efficient solar power generation.	Yet to be commercialised.
Hong Kong Polytechnic University, China: Perovskite and graphene in combination have produced inexpensive, highly efficient solar cells. The perovskite serves as active layer for harvesting the light, and the graphene acts as the transparent electrode material, replacing indium tin oxide.[100].	TRL 4-5	12% conversion, up from 7% for traditional semi-transparent cells.	Yet to be scaled up for commercial applications.
Helmholtz-Zentrum Berlin für Materialien und Energie, Germany: A	TRL 4	Silicon absorbs the red portion more	No indication of the (hopefully

"tandem" solar cell combining perovskite and silicon photovoltaic cells, to absorb more of the solar spectrum more effectively, has been enhanced through the use of graphene as a protective and transparent "frontal contact" layer over the fragile perovskite layer [101].		effectively; perovskite absorbs the higher-energy portion of the spectrum more effectively, leaving the red portion for silicon. Potential for more efficient solar cells.	improved) conversion efficiency is reported.
The Conversation, AUS, UK, USA, Africa, France: Trillions of small, organic photovoltaic cells are being touted as the answer to what will power the estimated trillions of sensors that will make up the IoT, and take just one day to earn back the energy invested in their production (versus 1 to 2 years for silicon cells) [102].	TRL 7-8	Cheap, flexible, can be moulded to 3D surfaces or integrated in clothing, are (more) effective at capturing diffuse light (better in low-light conditions), take just one day to pay for themselves (vs years).	Traditionally low conversion efficiency - improvements always welcome.
SLAC National Accelerator Laboratory, US: Manufacturing technique that could double the electricity output of inexpensive solar cells by using a microscopic rake when applying light-harvesting polymers. Polymers are forced through a slightly angled rake containing several rows of stiff microscopic pillars as they are painted on to the underlying conducting surface of the solar cell [103].	TRL 6-7	Potential doubling of the energy output of the "polymer" class of solar cells, which are cheaper to produce than conventional silicon-based solar cells, and can be painted or printed in place), and can be flexible.	Potential efficiency of 10% is still lower than the 20-25% of silicon solar cells. The technique still needs to be customised for blends of polymers other than the one used in this research, and adapted for industrial-scale roll-out.
Karlsruhe Institute of Technology, Germany: A new type of material, based on Metal-Organic Frameworks has both a high efficiency of producing charge carriers and high mobility of those charge carriers. It uses organic molecules of the type found in chlorophyll and hemoglobin, but rather than turning sunlight into chemical energy, it turns sunlight into electricity [104].	TRL 4	Such organic solar cells will be much cheaper than silicon-based cells due to the manufacturing process requires far less energy. These are also flexible, suitable for coating clothes or other surfaces.	Requires further development to be viable.
RIKEN, Japan: Scientists are investigating the mechanisms by which electricity is generated by light striking the interface between two organic materials, which combinations perform well, and why [105].	TRL 3-4	Improved efficiency in polymer/ organic solar cells, and all the other benefits that go with them - lower cost, flexibility etc.	
University of Copenhagen, Denmark: Material that stores solar energy by changing the shape of molecules. They then change back on demand, releasing their stored energy (e.g. as heat). The new material has doubled the energy density of previous materials, and the molecules can hold their changed shape for hundreds of years [109].	TRL 4	An alternative to electrochemical batteries or thermal storage in solar concentrators. Has none of the disadvantages of electrochemical batteries (such as the toxic compounds used).	Despite the advantages in energy density and stability of the molecules in the new material, an efficient mechanism for changing the molecule shape back again (releasing their energy) on demand is yet to be found.
Karlsruhe Institute of Technology, Germany: A new type of material, based on Metal-Organic Frameworks (metal node points and organic molecules), has been discovered that has both a high efficiency of	TRL 4	If suitably developed, organic solar cells will be much cheaper than silicon-based photovoltaics because the	Inference is that the efficiency of turning sunlight into electricity is still low.

producing charge carriers and high mobility of those charge carriers. It uses organic molecules of the type found in chlorophyll and hemoglobin, but rather than turning sunlight into chemical energy, it turns sunlight into electricity [104].		manufacturing process requires far less energy. These are also flexible, suitable for coating clothes or other surfaces.	
Helmholtz Association of German Research Centres: An inkjet 3D printing technique for printing a type of thin film solar cell, called a kesterite solar cell. The reduction in waste and the printing technique itself has significant advantages for industrial production [106].	TRL 5	Negligible waste during manufacturing; the method is suitable for large scale production of this type of cell. The material itself is low toxicity, which is a good thing.	With a conversion efficiency of 6.4%, it is at about half the efficiency of the record for this material (although team is working on improving this).
Bilkent University, Turkey: Nanowire solar cells with curled nanowires increases the amount of light they can capture while reducing the total substrate area required by 50% [107].	TRL 3	Potential increases in solar cell efficiency.	Improvements in power output not quantified. Low TRL technology.
Georgia Institute of Technology, US: A first of its kind 'optical rectenna' has been devised, comprising nano-scale tubes, in this case carbon nanotubes, which act as antennas for light. They generate an oscillating charge when waves of light are incident upon them, which can be converted to electricity through attached rectifier devices [108].	TRL 4	The promise (as claimed by the researchers) is to "ultimately make solar cells that are twice as efficient at a cost that is ten times lower".	A bold claim - efficiency is thus far less than 1%. Remains to be seen if future advancements and optimisations can make them cost-competitive with conventional and other emerging photovoltaics.
Artificial Photosynthesis			
Caltech, US: An efficient, safe, integrated solar-driven system for splitting water to create hydrogen fuels. The system has three main components: two electrodes (a photoanode and a photocathode) and a membrane. The photoanode uses sunlight to oxidize water molecules and generate protons, electrons and oxygen. The photocathode recombines protons and electrons to form hydrogen gas. The plastic membrane keeps the oxygen and hydrogen gases separate (mixing and accidental ignition can result in an explosion). The complete system uses a layer of TiO_2 to prevent corrosion of a gallium arsenide-based photo-electrode [110] [370].	TRL 4	Cheap and widely available materials are used for the system, such as TiO_2 catalyst for the water-splitting reaction. All components are stable under the same conditions. The new system improves on previous records for safety, performance and stability for artificial leaf technology by a factor of 5-10.	Further research is required to extend lifetime of the system and to develop methods for cost-effective manufacturing and safe storage of hydrogen.
Lawrence Berkeley National Laboratory, US: A hybrid system of semiconducting nanowires and bacteria that mimics the natural photosynthetic process by which plants use the energy in sunlight to synthesize acetate from carbon dioxide and water. Acetate is the most common building block today for biosynthesis [111].	TRL 4-5	Capture of carbon dioxide emissions before they are vented into the atmosphere coupled with production of valuable chemical products, including biodegradable plastics, pharmaceuticals and liquid fuels (which can be created through	Yet to be developed to commercially practical level.

		additional processes on the acetate).	
Manchester University, UK: Researchers have developed a new synthetic pathway for the biosynthetic (a.k.a. renewable, not petroleum-derived) production of propane, through modification of enzymes used in existing fermentative butanol production. The engineered enzyme redirects the microbial pathway to produce propane instead of butanol [112].	TRL 4-5	Propane has good properties that let it be stored and transported in compressed liquid form at room temperature. This has implications for in-situ production of fuels. Also, a viable fuel for things like solid-oxide fuel cells, and for heating.	Currently, little or no propane fuel is used within ADF. Plus, this method seems some way from being able to produce commercial quantities.
Nuclear fusion			
Lockheed Martin: Claim of a major breakthrough in containment technology for nuclear fusion reactors. The ‘magnetic bottle’ demonstrated can contain the generated heat (which reaches hundreds of millions of degrees) [10].	TRL 2-3	This is a step toward creating a small size compact fusion reactor.	There is a lot of scepticism in the scientific community about cost-efficiency of nuclear reactors. The company hasn’t published any scientific papers on this work.
MIT, US: Claim that the new commercially available superconductors (rare-earth barium copper oxide superconducting tapes) can be used to produce high magnetic field coils - the stronger magnetic field makes it possible to produce the required magnetic confinement of the superhot plasma, the working material of a fusion reaction. The new reactor is designed for basic research on fusion and also as a potential prototype power plant that could produce significant power [117].	TRL 2	Cheaper, smaller, more efficient fusion reactors. Claims that the new design with the new superconducting material will provide a 10-fold boost over existing superconducting materials. The basic reactor concept and its associated elements are based on well-tested and proven principles developed over decades of research.	Yet to demonstrate a sustained fusion reaction (using this design or any other design) that releases more energy than is required to initiate it.
University of Gothenburg, Sweden & University of Iceland, Iceland: Claim that both heat and electricity generators could be created within a few years, utilising a novel type of nuclear fusion that produces almost no neutrons, but instead muons (fast, heavy electrons that decay quickly into normal electrons) directly [118].	TRL 3	Advantages in terms of the type of fuel required (less dangerous to handle)	A proof-of-concept prototype yet to be created.
Wireless power transmission			
KAIST, South Korea: Wireless power transfer (WPT) technology that allows mobile devices to be charged at any location and in any direction, so long as mobile users stay in a designated area where the charging is available, e.g., the Wi-Power zone. The invention is based on Dipole Coil Resonance System (DCRS) which was developed by the team in 2014 for inductive power transfer over an extended distance [121].	TRL 5	Solves some of the current limitations of wireless charging technologies: small charging distance, directionality, size/complexity of transmitters and receivers for 3D omnidirectional operation. More flexible than current wired and wireless charging mechanisms. Apparently safe for	Less efficient than conventional wireless (or wired) charging technologies.

		humans based on existing standards of non-ionizing radiation exposure.	
Tongji University, China: Improved efficiency of wireless power transfer from a few percent to 20% over a distance of 4 cm. This was achieved through embedding magnetic metamaterials into the coils used in non-radiative wireless power transfer (the method used in most such applications, e.g. rechargeable electric toothbrushes and Apple Watch) [119].	TRL 4-5	Useful for recharging small, portable gadgets and wearable electronics. The authors cite rechargeable pacemakers and electric vehicle charging as potential applications.	20% efficiency still isn't as good as the near-100% from a wired connection, but may have its niche.
ITMO University, Russia: A novel wireless charging technique has been developed maintains up to 80% efficiency at distances of 20 cm. The novelty is in replacing copper coils with spherical dielectric resonators made from ceramic material – avoiding losses in metals, and the use of a higher-order resonant frequency mode called a magnetic quadrupole. Also doesn't require as precise alignment/orientation [120].	TRL 4-5	Improvement is expected through continued development.	Range and power limitations remain in the current prototypes.

Appendix B Horizon Scan for Transportation Technology

Examples	TRL	Applications and Benefits	Challenges and Barriers
Autonomous and semi-autonomous vehicles			
Google (Alphabet Inc. subsidiary): In 2014 Google revealed the Citymobil prototype for smaller, low-speed (under 30kph) vehicles without any human steering control. These were designed to address the safety issues raised with driverless vehicles [122]. Since then, the company formed more partnerships with established automakers and suppliers to accelerate its work on self-driving cars [359].	TRL 7	Potential for improved safety on the roads, reduced congestion and pollution, and more mobility options for the elderly and the disabled.	In 2016, a Google self-driving car caused its first (minor) accident by striking a bus. While the allocation of blame remains somewhat unclear, the media response [123] reflects the considerable distrust in autonomous systems. A clear legal framework is yet to be established.
Volvo: Self-driving 'Concept 26' sedan is expected to be released commercially in Sweden in 2017. It has a bucket-style seat design that actively cradles the driver during transition between its three modes: Drive, Create or Relax [125].	TRL 7		
Freightliner (Daimler subsidiary), US: 'Inspiration Truck' self-driving model was unveiled as the first road-legal self-driving truck. It uses Daimler's 'Highway Pilot' technology based on a combination of radar, stereo computer vision and other sensors. Same technology is used in the previously reported Mercedes Future Truck 2025 [128].	TRL 7	The company is framing the dialogue around reducing crashes caused by driver fatigue.	There is no mention of price or timeframe for commercial availability. Further road tests will take place in Nevada.
Google, Uber, Nissan, General Motors, a ride-sharing service Lyft and a start-up Zoox: Aiming to put fully autonomous taxis on the market [129, 130].	TRL 5-6	Studies have shown the potential to reduce greenhouse gas emissions from taxis by up to 82% [371].	Similar to other driverless vehicles.
Robotnik: Developed a self-driving car for research and cargo delivery in restricted environments. It can navigate autonomously, or be tele-operated. The vehicle can carry two people plus 150 kg, has 70 km range and speed of 32 km/h [131, 349].	TRL 7-8	Potentially useful for cargo delivery, logistics distribution in reasonably structured controlled environments. The system works with open architecture based on ROS (Robot Operating System) – and open source modular operating system for robots.	Limited ability to autonomously navigate in unstructured environments.
Toyota in collaboration with MIT and Stanford: Development of assistive autonomy with driver in control most of the time. Autonomy will step in if it detects a dangerous situation [126]. Toyota have committed to investing $1bn over 5 years and plans to	TRL 2	Reducing crashes and associated injuries.	Transition to military unstructured environments is challenging.

open an R&D lab in silicon valley [127].			
DARPA, US: Ground X-Vehicle Technology (GXV-T) programme aims to break the 'more armour' paradigm by making fighting vehicles more mobile, effective, safe and affordable. One of the programme objectives is semi-autonomous driver assistance and automation of key crew functions [360]. DARPA has awarded contracts to Carnegie Mellon University, Honeywell, Leidos, Pratt & Miller, QinetiQ Inc., Raytheon, Southwest Research Institute and SRI International [138].	TRL 4	Looking at enhanced mobility, agility, crew augmentation and signature management for future fighting vehicles.	Programme is in its initial stages; the technology does not yet exist.
DST Group, Australia & TARDEC, US: Bilateral trials for TORVICE (Trusted Operation of Robotic Vehicles in a Contested Environment). The vehicles have sensors and active speed regulators [135].	TRL 6	A range of potential applications in military operations, including logistic distribution tasks.	At this stage, a human driver still has to be present to take control if necessary.
TARDEC, US: Convoy Active Safety Technologies (CAST) and Autonomous Mobility Applique System (AMAS) programmes have demonstrated robotic follower vehicles operating at highway speeds over hundreds of kilometres [2, 133, 134]. OshKosh trucks sells the TerraMax conversion kit that can be used to retrofit a range of tactical wheeled vehicles into robotic assets capable of supervised autonomy in either leader or follower role. The kits include obstacle avoidance capacity and operation in GPS denied environments. The OshKosh system has been demonstrated for the US Marine Corps [136, 137].	TRL 7	Unmanned convoys give reductions in personnel and allow for lighter, cheaper vehicles. Tests have also shown that during long trips or in poor visibility conditions, the unmanned convoy systems are better than human drivers at avoiding obstacles and pedestrians.	Some operational limitations include trust in technology, cost of sensors, and vulnerability to electronic counter measures. Liability issues have not yet been addressed.
US Army: Looking at adopting vehicle-to-vehicle (V2V) communication technology that is already deployed on commercial vehicles. For example, Navistar, which supplies MaxxPro MRAP vehicles to the US Army, has deployed its OnCommand technology in commercial trucks. OnCommand allows the vehicles to communicate their health over air in real time in support of CBM [304].	TRL 7-8	Navistar's architecture strategy is not married to any specific telematics vendor, so remote diagnostics can be provided with almost any of them. According to the company, the customers get the benefits of reduced costs and better asset management including reallocation [304].	Testing required in military environment.
Aerial transportation			
US DoD: Precision air-drop involves air-dropped cargo guiding itself to a landing zone. The US Joint Precision Airdrop System (JPADS) uses an airborne guidance unit, electromechanical steering actuators, and a steerable canopy to guide payloads to their landing points.	TRL 9	The main classes of supply air dropped in Afghanistan in 2014 were food, water, and fuel. The technology allows reduction in the number of vehicles	Further development is required to increase precision of delivery. It is expected that precision air drop within a forward base's wire could be possible

JPADS family includes: Microlight: 10-150 lb; Ultralight: 250-700 lb; Extra light: 700-2,400 lb; Light: 5,001-10,000 lb; and Medium: 15,000-42,000 lb. All of these versions have been developed. The JPADS family of systems allows for drops from up to 25,000 ft and 25 km offset. From 25,000 ft the JPADS can hit a soccer-field sized landing zone within a 23 km radius cone of coverage. One aircraft dropping from one location can deliver payloads to multiple locations on the ground. Work is also ongoing to develop a helicopter sling load system to work with JPADS. This system can carry 32 low-cost, low-altitude airdrop systems, which are expendable air drop systems designed to open at 100-500 ft altitude. It could be modified to carry up to eight container delivery systems. It has been developed to interface with UH-72, UH-60, CH-47, and CH-53 helicopters and has been demonstrated on UH-72, CH-47, and CH-53 helicopters [139].		used reduces both the fuel and maintenance demands associated with operating these vehicles. JPADS eliminates some reliance on ground resupply and allows resupply to keep pace with expeditionary forces on the move.	within ten years.
Reaction Engines, UK: Developing the hypersonic Synergetic Air-Breathing Rocket Engine (Sabre) to power a vehicle from a standing start to Mach 5.5 in air-breathing mode, and from the edge of the atmosphere to low Earth orbit in pure rocket mode. A fundamental enabler of the concept is a complex heat-exchanger system made up of miles of fine tubing that allows oxygen to be taken straight from the atmosphere for use as fuel [141].	TRL 3	The company is developing the Sabre engine principally for the Skylon single-stage-to-orbit spaceplane. But the propulsion system and its pre-cooler technology are attracting wider interest for potential aircraft and two-stage launch vehicle applications. Potential is for rapid, long distance transport of critical materiel.	Payload constraints are yet to be clarified. The payload would be subjected to the extremes of temperature, pressure, acceleration etc.
DST Group, Australia: Joint US-Australia trials to demonstrate hypersonic travel at over five times the speed of sound. The Hypersonic International Flight Research Experimentation (HIFiRE) programme aims to fly with a hypersonic engine at Mach 7. In a recent trial, the experimental rocket reached altitude of 278 km with target speed of Mach 7.5 [140].	TRL 4-5		
Martin Aircraft Company, NZ: The Martin Jetpack [142] previously reported in earlier scans is on sale and has just been approved for human use in New Zealand. Targeted at the 'first responder' community, not yet the leisure community [143].	TRL 7-8	Provides VTOL capability, can travel for over 30 minutes at 74 km/h at an altitude up to 1000 m. Payload of up to 120 kg. Can be piloted remotely.	
Aeroscraft: ML866 model has 60 ton payload and is already in use. Models in development include ML868 (250 ton payload) with optimum altitude of 1000 m and requires 360 m diameter space for	TRL 6-7	The technology offers alternative to hub and spoke logistics with ability to transport goods between almost any	Large, high-value target

landing and ML86X with 500 tons payload [145]. The company Hybrid Air Vehicles has similar offerings [144].		locations.	
Tyres			
Michelin, US: X Tweel Airless Radial Tyre is a combination of an outer rubber tread supported by flexible spoke system which gives a suppressing effect [146].	TRL 7-8	This type of tyre has no leaks or punctures, has higher lateral strength, better stability and better durability on partial damage. Currently produced for construction, farm and lawn equipment.	Lack of dynamic adjustability, suffers from vibrations and heat build-up at higher speeds; more expensive; debris may interfere with spokes; uncertainty over speed profile for larger tweels.
McLaren, US: Semi-pneumatic solid cushion tyres use three layers of rubber compound and multiple shock-absorbing relief holes to from the puncture-resistant tyres. Different patterns are available for different vehicles, backhoes, loaders, fork lifts, etc. [147].	TRL 7-8	Puncture resistance and longevity; softer, flexible compounds on the inside; 4-5 times longer life; deeper tread depth for traction; increased weight for greater lifting ability.	Not yet transferred to military applications.
Big Tyre, Australia: Mining Wheel third prototype was tested in 2014 with a load of 12 tonnes. It was shown to have significant reserve strength and be highly impact resistant [149].	TRL 6	The tyre is expected to handle a greater load than pneumatic tyres of equal size.	Uncertainty over high-speed use and terrain interference challenges.
Google (Alphabet Inc. subsidiary): Shweel has shock absorbers as wheel spokes between wheel-hub and rigid rim. It is in use for bicycles and wheelchairs, but not for cars [148].	TRL 9	Enhancing survivability by replacing vulnerable pneumatic tyres and reducing logistic burden for replacement tyres.	Immature technology for automotive applications; may reduce off-road mobility due to lack of flexibility in tyre types for different terrains.
SciTech Industries: Omega-shaped, glass fibre-reinforced PET springs used to generate structural strength and form without inflation [150].	TRL 6-7	Springs can be tailored to meet a wide variety of demands; attaches to standard rims; similar weight to standard tyre; can sustain multiple impacts from road hazards; robust on loss of several springs; runs 'cool' without heat build-up; boosts fuel efficiency by 2%.	Pilot testing stages.
Containers			
RDECOM, US: Developed Joint Modular Intermodal Distribution System (JMIDS) which are standardised multimodal modular containers that lock to intermodal platforms [151].	TRL 8	Rapid, efficient, seamless handling and distribution of military supplies; facilitates air/land/sea-based distribution without reconfiguration; eliminates tie-down requirements.	

Appendix C Horizon Scan of Automated and Autonomous Systems

Examples	TRL	Applications and Benefits	Challenges and Barriers
Unmanned Aerial Systems (UAS) - Countermeasures			
Lockheed Martin: ICARUS system allows the operators to identify, track and engage threat UAS with electronic and cyber warfare capabilities. The company claims that ICARUS can disable UAS onboard cameras, knock the UAS out of the sky, or confiscate UAS control and land it in a safe zone. Similar systems include Selex ES's Falcon Shield and Blighter Surveillance Systems' AUDS [12].	TRL 7-8	Protection from enemy UAS for military operations, including ability to capture the UAS for further examination.	Cost and complexity; cyber safety.
Boeing: Portable Compact Laser Weapon System is a 2kw laser that was demonstrated to shoot down a UAS during Exercise Black Dart in California. The effect was similar to having a welding torch applied to the target but from hundreds of metres away [154].	TRL 6-7	Portable anti-UAS system.	Ability to maintain the laser on the target for required period of time; power requirements.
US Army: Adapting existing counter aerial systems to shoot down UAS. The missile-based Counter Rocket, Artillery, and Mortar (C-RAM) has been used to intercept a UAS at over a kilometre range during a test (as part of the Enhanced Area Protection and Survivability, or EAPS project). The EAPS ARDEC gun alternative envisions a 50 mm cannon to launch command guided interceptors. The system uses a precision tracking radar interferometer as a sensor, a fire control computer, and a radio frequency transmitter and receiver to launch the projectile [155].	TRL 7-8	Long-range anti-UAS function.	Cost; requirement for ammunition.
OpenWorks Engineering, UK: SkyWall 100 bazooka-style device that uses compressed air launcher to fire smart projectiles at targeted drones with a range of 328 feet (100 m). The high-tech scope locks onto the UAS and an onboard computer tracks the target's flight path to calculate the required trajectory. A canister-like projectile opens when it reaches the drone and uses a net to capture it. A parachute is then deployed to bring the drone down safely [156].	TRL 6-7	Safe capture of drones allows for forensic investigation and/or re-use.	The system has a relatively short range and is not likely to be effective against a swarm of drones.
Malou Tech, France: M200 drone that can capture smaller unmanned drones with a net [157].	TRL 6-7	Potential applications are in law enforcement.	Establishment of regulatory frameworks; accuracy of net deployment.
Northrop Grumman, US: Northrop Grumman have demonstrated	TRL 7	Platform agnostic – can be integrated	This only tracks and targets the drones.

their Lightweight Laser Designator Rangefinder, a ground based targeting system that can recognize targets in day, night or obscured conditions, range to the target at an eye-safe wavelength, and calculate grid coordinates for precision targeted fire support [158].		into a wide variety of platforms	It relies on other systems to actually stop them.
Michigan Tech University, US: Octocopter that can shoot a net up to 40 feet to snag smaller drones and deliver them to the ground. Similar concepts have been used in Japan and South Korea [159].	TRL 6	Expected applications in law enforcement.	Accuracy
Battelle Memorial Institute, US: An anti-drone gun has been developed that doesn't fire projectiles, but rather jams GPS and RF communications, in theory causing commercial drones to lose control and land (relying on confusing a drone and causing it to rely on a lost-link protocol that makes it land) [160-162].	TRL 6	Small, lightweight. A way of stopping drones without risking injury to bystanders by using kinetic means. Useful in law enforcement, perimeter protection tasks.	Easy to overcome by modifying or removing the 'lost-link' behaviour.
UAS – Small			
Tactical UAS: • Aero Vironment's RQ-14 Dragon Eye • Israel Aerospace Industries' Mosquito • CU161 Sperwer • CU167 Silver Fox [122].	TRL 9	ISR tasks; high stealth systems; medium manoeuvrability.	Low weight, lift capacity, speed, and endurance.
AeroVironment: Blackwing – a small, tube-launched UAS that deploys from under the surface of the sea on manned and unmanned submarines. Blackwing has advanced, miniature electro-optical and infrared payload, selective availability anti-spoofing module GPS and a secure digital data link [163].	TRL 6-7	The Joint Capabilities Technology Demonstration was completed in September 2015 with a strong recommendation to transition into the fleet for integration with a range of surface vessels and ground vehicles.	
US Army is looking to provide Soldier Borne Sensors (SBS) mini-drones for soldiers. Currently deployed Prox Dynamics' Black Hornets weight 18 g (1.3 kg with the controller). It can fly for about 25 minutes at up to 11 miles per hour and has a line-of-sight range of 1600 metres. Cameras can be aimed and send live feed to the controller; it is also possible to take more detailed still shots [372].	TRL 9	Improved situational awareness at tactical level.	Black Hornets are individually hand-made, which makes them more expensive.
DJI: Phantom 4 now has five cameras and software for 3D modelling of its surroundings. This enables the drone to avoid obstacles such as walls and bridges. The ActiveTrack feature allows the user to trace a circle around a subject and the 3D model of that subject enables the UAS to track it to keep it in the frame [373].	TRL 7	Improved ability to navigate in complex environments.	These types of drones are now used by non-state actors in a number of countries.
Startup Skydio: Developed a sophisticated autopilot for drones that includes obstacle avoidance and allows the UAS to orientate itself	TRL 7		

and navigate through busy areas. The technology uses several video cameras for mapping and navigation at high speeds [374].			
Wal-Mart: Applied to US regulators for permission to test drones for home delivery, curb-side pickup and checking warehouse inventories in October 2015. The retail giant plans to use the drones to fill and deliver online orders [164].	TRL 6	Large retailers such as Walmart and Amazon are now looking to drones to improve efficiencies in stock management, transportation and deliveries.	Federal regulators are still assessing rules for commercial operation of drones.
Swiss Post, Swiss World Cargo and Matternet: Trials of a drone-based postal delivery service in Switzerland. The Matternet ONE drone can transport up to 1 kg for over 10 km. The drones follow secure flight paths defined by Matternet's own cloud software [165]. Mail delivery demonstration was also completed from mainland Singapore to an island using Pixhawk Steadidrone quadcopter [167, 375].	TRL 7-8	In additional to premium postal deliveries, the drones are being considered as distribution mechanism for isolated areas. In military setting, this approach also reduces danger for the troops.	Swiss Post states that the trials will not lead to a commercial service in less than five years and are not expected to replace the traditional delivery method. Clarification of regulatory requirements and overcoming of technical obstacles is still needed. Limited range and payload capacity.
Flytrex Sky: GPS-guided quadcopter designed to carry small loads. It has eight hooks for small items (cans, sandwiches, etc.). It is connected through 3G and both sender and receiver can guide it through a smartphone app. When upgraded with an optional second battery, Flytrex can fly for up to 35 minutes [166].		The basic Flytrex Sky is sold for $749, making it a relatively low cost delivery option.	
A Dutch engineering student has developed an airborne defibrillator delivery drone that weighs under five pounds and has a range of five square miles [10].		Similar drones could carry additional medical supplies and provide comms links with medical personnel for guidance until further help arrives.	
DHL: Recently began parcel delivery (including emergency medications) to a small island 12 km off the German coast using mini UAV [376].			
Harvard University, US: RoboBee uses an electrode patch and a foam mount for absorbing shock. The robot weights 100 mg, takes off and flies normally. When the electrode patch is supplied with a charge, it can stick to almost any surface via electrostatic adhesion. This allows the RoboBee to perch and save energy [168].	TRL 4	The electrostatic system doesn't cause destabilising forces during disengagement. The patch requires approximately 1000 times less power to perch than to hover, thus allowing extension of operational life [168].	Researchers are working on integrating onboard batteries. Currently, can only perch on ceilings and overhangs. The team is looking to amend design to allow perching on any surface [168].
University of Maryland, US: A new revision of Robo Raven, Robo Raven V is a hybrid platform that uses both propellers (like an airplane) and its flapping wings to fly. The new propellers provide	TRL 6	Higher payloads, longer flight times than previous iterations. Potential utility in carrying/delivering small	Utility in a military context is yet to be determined.

extra thrust which in turn leads to much higher lift forces. The added capacity means Robo Raven V can incorporate a larger battery to increase its flight endurance or carry more sensors. It now also has a claw, so it can grasp and release objects during flight [377, 378].		quantities of material/materiel.	
UAS – Medium			
Boeing: ScanEagle is a small, low-cost, long-endurance UAS that has been used for ongoing ISR with missions averaging 22 hours per day. A rail-launched system with range of 100 km/several hours [170, 379].	TRL 9	Have been used by ADF in Afghanistan from 2007, completing over 32,000 flying hours in over 6,200 sorties [379].	"Launch-and-land" UAS are difficult to return to the air once they've landed and delivered the payload.
Advanced Ceramics Research's Silver Fox is a rail-launched UAS that ranges up to 100 km/several hours. Silver Foxes have been purchased by the Canadian Forces [170].	TRL 9		As above.
AAI: Shadow UAS are used by the Australian Army with high-resolution cameras. These fly above patrolling troops to provide detailed real-time information about activities on the ground. They have eight hours endurance and are rail-launched [170].		The US Quick-Meds program has conducted demonstrations with Shadow UAS dropping 9 kg of medical supplies to forward areas.	
Mist Mobility Integrated Systems Technology Inc. (MMIST): CQ10B autogyro that can carry 1088 kg up to 150 km, placing loads within 30 m of a predesignated point and then performing near vertical take-offs [171]. The original CQ-10A Snowgoose is a self-guiding parafoil UAS that can be air-launched from C-130 Hercules aircraft, or ground-launched from a HMWVV or flatbed truck. It can carry up to 250 kg payload for up to 800 km [170].	TRL 7-9	Systems like Snowgoose are ideally sized for discrete delivery of small quantities of logistic supplies and are less expensive than most other unmanned cargo transport systems under development [171].	Further research challenges include autonomous take-off and landing algorithms, hybrid powered and unpowered autogyro mechanism for take-off and landing, and advanced power and flight control algorithms [380].
UAS – Large			
Northrop Grumman's MQ-8 Fire Scout and Boeing's A160 Hummingbird rotary wing systems have medium weight and lift capacity and medium manoeuvrability [122].			Low speed, endurance, and stealth
US Marine Corps: Received their first two Kaman K-MAX helicopters for cargo distribution with maximum payload of 6,000 pounds. The helicopter has interlinking rotors and can fly itself [172].	TRL 9	Primary mission is to provide cargo load operations. Proven in three years of operations in Afghanistan. Recently demonstrated in firefighting scenarios, including cargo drops, water drops, and progressive line building with a bucket [143].	Cost; maintaining communications in contested in degraded environments; cyber security.
Lockheed Martin's Skunk Works: Leading a team with Piasecki Aircraft to develop the next generation of compact, high-speed VTOL delivery systems under the ARES programme (following on from the	TRL 5-6		Prototype yet to be tested.

Transformer TX programme) [381]. ARES is a vertical take-off and landing delivery system that will be unmanned and is expected to support multiple payload configurations from a common airframe. ARES was in its third and final phase of research and development as of February 2014 [139].			
In 2014 Sikorsky, under the Manned/Unmanned Resupply Aerial Lifter program with the U.S. Army, demonstrated its capability on its existing fleet of Sikorsky autonomous research aircraft being operated remotely by a pilot on the ground. Sikorsky has developed a platform-independent flight control system that was initially developed for commercial offshore oil industry applications and has been refined for military operations [139, 382].	TRL 7	Platform-independent kit that provides autonomous capability.	
UAS – High Altitude Airships (HAAs)			
Lockheed Martin: The HAA and its sub-scale demonstrator, the High Altitude Long Endurance-Demonstrator (HALE-D) are un-tethered, unmanned lighter-than-air vehicles designed to operate above the jet stream in a geostationary position to deliver persistent station keeping [175].	TRL 6-7	Potential applications include communications relay, ISR, hub for a ballistic missile defence system, refuelling station, or airstrip for other planes and drones [15].	
Northrop Grumman: Long Endurance Multi-Intelligence Vehicle (LEMV) concept for a vehicle with high weight and size lift capacity [122].	TRL 4-5		Low speed, endurance, stealth and manoeuvrability.
UAS – Swarms			
Pentagon, US: Recently declassified a video that shows F-16 fighter jets releasing micro-drones from its jet's flare dispensers while flying at 692 km/h. They are encased in canisters that parachute to the ground, break open and release the drones which then come together to form a swarm [181].	TRL 6	Effective offensive effect that expends adversary's ammunition and is difficult to counter.	Similar technology is likely to be developed by potential adversaries.
Office of Naval Research (ONR), US: Developed a prototype UAS that can be launched through a tube using compressed air with the aim of overwhelming the adversary. The program is Low Cost Unmanned Aerial Vehicle Swarming Technology (LOCUST) [184, 185].	TRL 6	Low-cost, unmanned, expendable, able to be mass-produced, can be launched from other unmanned platforms.	Small payload size, no indication of range or endurance. Potential threat to logistic installation if similar systems are used by adversary.
DARPA, US: "Gremlins" programme looking to develop the technology to launch swarms of low-cost, reusable UAS over great distances and then retrieve them in mid-air. The gremlins themselves are somewhere in between disposable drones and conventional	TRL 2-3	DARPA wants each gremlin to be able to fly a few dozen missions at most, making them more cost effective than disposable systems but also cheaper	Mid-air retrieval is the most significant barrier at this stage, but not such a problem if the Gremlins are designed to be expendable/disposable.

drones that are intended to last for years or decades [182, 183].		than bigger, more complex drones that need continuous maintenance.	
Queen B Robotics: Demonstrated software for controlling a swarm of rotary-wing UAS including single-user control of the swarm, coordinated flight, collision avoidance, synchronised motion, drone-to-drone communication including information relay via private network. The UAV used in the demonstration has a 6-mile flight range. The company provides custom app-based swarm control software for applications including Search and Rescue, Wildlife Surveillance and Monitoring, Security systems for your property, Real-time data acquisition from remote locations, In-flight interaction software, 3D Mapping and Delivery Systems [162, 186, 187].	TRL 8	Redundancy and resilience through use of multiple drones; control of multiple drones by a single user.	Potential for use by adversary.
Naval Postgraduate School in Monterey, California, US: Record for control of 50 drones by a single operator with use of algorithms such as 'follow me', and for search and rescue [188, 349].	TRL 7	Potential applications in search and rescue operations.	Potential for use by adversary.
UAS – Hybrid			
Johns Hopkins University, US: Corrosion Resistant Aerial Covert Unmanned Nautical System (CRACUNS) that can stay under water for months without deteriorating or decaying. When activated by a signal, the CRACUNS can rise to the surface and begin flight. The UAS body does not have any structural metal parts or machined surfaces [176].	TRL 5	Potential military applications in pre-positioning the drones for further missions on command.	The report doesn't mention anything about drones being able to swim under water to position themselves in the correct location.
Naval Research Laboratory, US: Merging unmanned undersea vehicles (UUVs) and UAS research in order to improve tactical availability of UUVs in time critical situations. The project is developing flying UUV techniques and technologies for long-range air delivery of UUVs and investigating configurations for mixed-mode use of bio-inspired fins in both water and air environments [177, 178].	TRL 5	UUV emplacement speeds are slow when long duration is required whereas UAV speeds are relatively fast and efficient. A flying emplacement is also not affected by high sea currents, opening the options for difficult-to-access areas.	Early prototype can only fly then swim, not the other way around. Requires further research and development.
US Army: Recently demonstrated autonomous resupply through UGS underslung from UAS using the Lockheed Martin K-MAX helicopters [180].	TRL 7	Increased options for resupply across varying terrain.	
Technical University of Denmark: Prototype of a new hybrid drone with high precision navigation, which manoeuvres with an accuracy down to five centimetres. It is capable of flying as a traditional multirotor/helicopter, an ordinary fixed-wing aircraft and has vertical take-off and landing capability as well as flying long range at	TRL 8	This type of drone combines the hovering and precision landing of a rotary-wing drone with the speed and endurance of a fixed-wing drone, and overcomes some of the problems with	

relatively high speed [383].		competing designs like the tail-sitter design, which is notoriously difficult to control in the transition between rotary/fixed wing modes of flight.	
University of California, US: H^2Bird is an ornithopter (flapping wing) micro vehicle. It is launched off the VelociRoACH UGV. The idea is to combine the efficiency and endurance of a ground robot with the range and versatility of a flying robot [179].	TRL 5	Overall decrease in cost of transport for both robots; improved stability.	The advantages of this combination evident at this scale do not necessarily extend/translate to larger scale vehicles - remains to be demonstrated.
Unmanned Ground Systems (UGS) – Small robots			
iRobot, US: 110 FirstLook is a five-pound, compact robot that provides situational awareness, can perform persistent observation and can investigate and manipulate dangerous and hazardous materials. iRobot received $4 million contract from US Navy for the 110 FirstLook models with deliveries to be completed by February 2016. [189].	TRL 8	FirstLook can integrate various sensors for HazMat, CBRN missions and supports thermal imagers. It can be equipped with a Small Lightweight Manipulator to interact with the environment. It is light and rugged, allowing it to be thrown through a window or down stairs [189].	Soldier UGS systems sometimes act erratically when faced with overlapping frequency bands, radio interference or jammers used to prevent IED detonation [15].
iRobot, US: The Small Unmanned Ground Vehicle (SUGV) is a man-portable robot with dexterous manipulator for dismounted mobile operations. It is a smaller and lighter version of the iRobot PackBot. iRobot has received a $9.8 million order from the US Marine Corps System Command for 75 SUGV robot systems with deliveries to be completed by Q2 2016 [190].	TRL 8	SUGV can enter areas that are inaccessible or too dangerous for people to provide situational awareness. It can be used by infantry, combat engineers, explosive ordnance disposal technicians and other personnel [190].	
Stanford University, US: Research on limits of friction in design of very small robots that can pull thousands of times their weight, climb vertical surfaces like gecko lizards or mimic bats. The design of their micro-robots focuses on synchronising smooth application of very small forces [384] [385, 386].	TRL 4	Their team of six microTug robots weighing 3.5 ounces in total have been demonstrated to move a 3,900 pound car with use of special adhesive inspired by gecko toes.	Very slow movement; works only on glass or similar substances that allow sufficient surface area for adhesion.
NASA, US: Developing a UGS called the Mojave Volatiles Prospector (MVP), as a test bed to develop the technologies and procedures that will be needed to search for water ice and other volatiles that might be hidden under the surface of the Moon, Mars or another planetary body (including the Earth). It uses various sensors including neutron spectrometers to detect the hydrogen in water and near-infrared spectrometers to detect the hydration and mineralogy of surface and	TRL 5-6	In-situ resource scavenging has potential to substantially reduce logistic burden.	Development of enabling technology for a test bed (no fully functional prototype yet).

subsurface materials [191, 192].			
Harvard University, US: Two robot designs for traversing uncertain terrain: one that deposits expandable, self-hardening foam and another that drags and piles up sandbags. Because the algorithm is adaptable, it doesn't matter whether the uncertainty that a robot confronts comes from the environment, a material, or another robot's behaviour [193].	TRL 6	These robots work with materials that are highly unpredictable. The system is applicable for any climbing, manipulating robot that's using any unpredictable materials, not just foam or sandbags. The system can work with multi-robot teams.	
MIT, US: Printable origami robot that folds itself up from a flat sheet of plastic when heated and measures about a centimetre from front to back. Weighing only a third of a gram, the robot can swim, climb an incline, traverse rough terrain, and carry a load twice its weight. Other than the self-folding plastic sheet, the robot's only component is a permanent magnet affixed to its back. Its motions are controlled by external magnetic fields [387, 388].	TRL 4	A step toward exploring implantable robots inside the human body.	Impractical outside of a laboratory environment due to the requirement for control via external magnetic fields. Not yet fully dissolvable - permanent magnet remains, and either acetone-soluble or only partially water-soluble.
Unmanned Ground Systems (UGS) – Robotic mules			
DARPA's Legged Squad Support System (LS3) is a rough-terrain robot designed to travel with unmounted soldiers. Each LS3 carries up to 180 kg of gear over 30 km mission lasting 24 hours. LS3 prototypes were tested with a detachment of Marines in Hawaii in 2014 [194-197].	TRL 6	The systems are designed to assist with load-carrying, evacuation, and power supply.	Following purchase of Boston Dynamics by Google, the LS3 research programme was divested in 2015.
MIT's Cheetah robot is now untethered and capable of operating outdoors. The robot runs on batteries and electric motors and is quiet (unlike Boston Dynamics LS3 and variants that run on petrol and hydraulics) [198].	TRL 5-6	Quiet operation.	Improvements required in handling complex terrain.
Israeli Aerospace Industries: Fielded REX 4x4 robotic logistic carrier in 2009. It has 250 kg payload capacity, can follow soldiers on rough terrain using a 'follow-me' function, goes at maximum speed of 21 km/h and can operate over 100 km or 72 hours. It can follow operator autonomously using GPS [199].	TRL 8-9	Hybrid electric system allows for silent operation.	
Lockheed Martin: Squad Mission Support System (SMSS) is a large, gas-powered, amphibious, high mobility six wheel all-terrain vehicle. The system is normally tele-operated, but also has voice control, follow-me, retro-traverse, GPS waypoint navigation, and road following modes [200, 389]. Lockheed Martin MULE has wheels mounted on articulated legs to increase mobility [390].	TRL 7-8	Multi-functional vehicle designed for a variety of military tasks.	Yet to be proven in missions.
Dispatch, US: Trialling 'Carry' robots that self-navigate sidewalks at a	TRL 6-7	Last-mile local delivery solution for	The company is yet to find effective

pedestrian pace with use of cameras, lidar and laser range finder, as well as modern AI techniques for learning. The vehicles have four locking compartments to store the package or mail to be delivered. The recipient receives mobile notifications when the vehicle is en route and uses a code to unlock the compartment [201].		small payloads.	commercialisation pathway [201].
Unmanned Ground Systems (UGS) – Warehouse robots			
US RDECOM: Looking to develop applique kits that can be added to standard MHE for enhanced manual and autonomous operations. It is expected that one operator should be able to control up to five forklifts [151].	TRL 4	Enhancing throughput; reducing required manpower; removing personnel from hazardous environments; providing mature code base for future autonomous systems.	Project in early stages.
Kiva Systems (Amazon subsidiary), US: Uses thousands of autonomous robots that deliver products within the ten Amazon mega-warehouses [202].	TRL 8	Efficiency, accuracy and speed of warehouse operations.	Kiva robot move whole shelves around, which requires a warehouse re-design.
MIT has developed an autonomous forklift capable of delivering and offloading supplies from a truck and can be operated via computer, or voice and gesture recognition.	TRL 8	Efficiency, accuracy and speed of warehouse operations.	Some concerns are occasionally voiced regarding safety in interaction with humans.
Leibniz University of Hannover, Denmark and STILL International: Developed an autonomous forklift capable of self-localisation based on laser mapping of roof structures. [203].	TRL 8	The forklift can recognize pallets using laser scanners (without them being at a pre-defined handover point).	Some concerns are occasionally voiced regarding safety in interaction with humans.
Vecna is developing an autonomous pallet handler (Rapid Palletising Robot (RPR)) with various levels of human robotic interaction. RPR system development was expected to be completed in 2015 and a pilot warehouse site will be established to explore the feasibility of this autonomous system to safely perform in a dynamic environment [204, 205].	TRL 7	Efficiency, accuracy and speed of warehouse operations.	Some concerns are occasionally voiced regarding safety in interaction with humans.
Clearpath Robotics have demonstrated OTTO, a "heavy load material transporter", that can fully autonomously move up to 1500 kg of payload around a warehouse [206].	TRL 7	More autonomous system that does not require any infrastructure to navigate (such as barcodes, lights, beacons or RFID tags). They can localise against an existing basemap and use LIDAR to adapt to changing environment.	Some concerns are occasionally voiced regarding safety in interaction with humans.
Magazino, Germany: Warehouse robot Toru that can pick up individual items of the shelves. It employs a 3D model of each warehouse in addition to a 2D map that it creates driving around the warehouse with two laser sensors. The data is shared with the other	TRL 8	The robot is designed to navigate freely between shelves and work with human workforce. It can handle novel objects and askew objects.	As is the case for most commercial warehouse robots, this system has not been tested in military context.

Toru robots working in the same warehouse. There are three types of Torus: Toru Cube is used for gripping single rectangular objects. Toru Box is for gripping standardised containers, boxes or trays. Toru Flex can pick up irregular shapes [207].			
Fetch Robotics, US: Built a robot called Freight as a co-worker in warehouses. The robots can follow the human workers around while an order is being selected and when it's complete take the load off to the next destination. At the moment, humans still have to do the physical picking. The company is also working on a second robot with a jointed arm on a wheeled base and a moving camera. This Fetch robot will be able to pick the items as well [208].	TRL 6-7	Unlike Amazon's Kiva robots, these can work within existing warehouses and use a laser scanner to integrate into existing operations. The robots give advantage of non-stop operations, ability to operate in more extreme conditions, and reduced shrinkage.	At the moment, warehouse robots mostly work in close teaming and supervision with human operators.
Exoskeletons			
Panasonic: Selling an exoskeleton that helps workers lift and carry objects. It weighs just over 13 pounds and attaches to the back, thighs, and feet, enabling the wearer to carry 33 pounds of extra load. The suit has a lightweight carbon-fibre motor. Sensors activate the motor when the wearer is lifting or carrying an object. The company, together with subsidiary ActiveLink, is also testing a larger suit designed to help carry loads as heavy as 220 pounds [209].	TRL 6-7	The device has been tested by warehouse handlers in Japan and is currently being trialled by forestry workers in the same region.	Power requirements; training requirements.
Cyberdyne, Japan: Selling exoskeletons for medical and industrial use. Their suit uses nerve signals to detect a wearer's intention to move before applying assistive force [209].	TRL 8	Medical and industrial applications.	
US Bionics: Working on commercialising two systems – one for rehabilitation and another for industrial use. The rehabilitation model is currently being tested in Italy [209].	TRL 6-7	The models are designed to be very lightweight and conform to a person's normal motion [209].	
ReWalk, US: Recently announced the latest version of its device for people with spinal cord injuries [209]. ReWalk has been available in Australia since 2015.	TRL 7	The system enables people who normally require a wheelchair to walk with the aid of crutches; does not require extensive training [209].	Expensive and bulky; requires crutches.
Harvard University, US: Developing soft exoskeletons using novel materials and methods of assisting a wearer's motion, making them lighter and more comfortable [209]. The sensors monitor the wearer's motion, and battery-powered motors move cables to pull up on the heel or on part of the leg near the hip. This adds a propelling tug at the right moment as the wearer steps forward [210].	TRL 5-6	Lightweight and efficient; may allow soldiers to carry heavy loads over long distances or help stroke victims walk more steadily. It doesn't disrupt normal walking and movement and can fit under clothes.	A big challenge is the amount of energy the devices use. More efficient batteries are required to reduce the weight further [210].
Perceptual Robotics Laboratory, Italy: Iron-Man-like wearable exoskeleton that allows users to lift 50 kg in each hand [391].	TRL 6	Applications include use in complex industry tasks such as managing jet	

		engines. They can help clear rubble after an earthquake, or be used for military use.	
USSOCOM: TALOS (Tactical Assault Light Operator Suit) programme began in 2013 and remains on track for delivery in 2018. It has in-built cooling and covers 60% of the body in armour. General Atomics are also working on a hybrid power supply that can switch to stealth battery mode when required [213, 214].	TRL 6-7	TALOS is designed to provide ballistic protection from small arms, low-light and thermal imaging sensors, and power-assisted limbs. Anticipated applications are in special operations.	Chemical/biological protection remains outside the programme scope. Further work is required to reduce the weight of armour and batteries.

Appendix D Horizon Scan of Materials and Manufacturing

Examples	TRL	Applications and Benefits	Challenges and Barriers
Additive Manufacturing			
General Electric: Completed a multi-year project to print a working jet engine using the Direct Metal Laser Sintering (DMLS) technique. The engine required some post-printing machining and polishing of parts. It was printed on an M270 industrial 3D printer from EOS. The machine can work with a variety of alloys including cobalt chrome, nickel alloy, titanium and stainless steel. The researchers had already built working aircraft components using DMLS method, including an FAA-approved part for a GE90 jet engine (metal housing for a sensor)[215].	TRL 5	The resulting engine went through numerous tests and was able to achieve 33,000 rpm.	Cost of production and finishing requirements.
Raytheon, US: Used commercially available high-end equipment and specially modified versions of low-cost 3-D printers to create 80% of the components of a guided weapon, including rocket engines, fins, parts for the guidance and control systems, and more. The goal is to print more complicated circuits in three dimensions with the very high resolution and performance of silicon [361].	TRL 7	Increased speed of rapid prototyping of new designs (hours instead of weeks), more advanced designs, printing on demand in the field.	Parts testing and certification.
Monash University and Amaero, Australia: Printed two metal jet engines that have all the working parts of a functioning gas turbine engine [215]. The demonstration has attracted interest from Airbus, Beoing, Raytheon, Safran and Microturbo [216].	TRL 3-4	Airbus, Boeing and Raytheon are now looking at collaborating with the Monash Centre for AM to develop new components with 3D printing.	The printed engines were proof-of-concept designs rather than parts for actual use.
GE Aviation: Uses printed metal alloy nozzles for its LEAP engine that have 5x more durability and weight 25% less than the previously produced nozzles made of 20 separate machine pieces [217].	TRL 8-9	Fuel savings due to weight reduction.	Parts testing and certification.
US Navy: Looking to test a flight-critical part made with a 3D printer – an engine nacelle and link attachment for a Boeing (VA) V-22 Osprey. The titanium part will be the first flight-critical 3D-printed part used by NavAir (Naval Air Systems Command) [219].	TRL 7-8	Greater responsiveness and shorter lead time for critical parts on operations.	Certification remains the biggest issue with months taking to certify a part that takes three days to print.
US Army Research Laboratory: Patent for a novel AM technology used to create micro-composites. These can be tailored to specific uses where high-strength lightweight materials are required. The process is Field-Aided Laminar Composite (FALCom). It uses electric fields to align and orient particles within a polymer system and can	TRL 4-5	The process allows 3D printing of structures with wiring, sensors or energy storage embedded in the structure. It also reduces total weight.	Practical applications yet to be tested.

be used to make multi-functional parts [220].			
US Navy: Using AM to make tools, moulding, repairs, prosthesis, cranial implants and custom parts as part of its Print the Fleet experiment. The designs are shared via the Navy Additive Manufacturing Technology Interchange (NAMTI) [217].	TRL 6-7		
US Army Natick Soldier Research, Development and Engineering Centre: Computer-aided Design and Rapid Prototyping Laboratory uses selective laser sintering to produce numerous prototypes and product components [220].	TRL 7-8	An example of products is prototypes for the pack frame of the Modular Lightweight Load-carrying Equipment (MOLLE) system and fabric attachments for the MOLLE pack. Rapid prototyping helps find design issues early on and continue to improve the products [220].	Cost of printers.
US Army: Rapid Equipping Force (REF) is deploying mobile AM labs in Afghanistan to quickly manufacture product replacements in the field. REF used two 20-foot, containerised mobile Expeditionary Labs (Ex Labs) to deploy to units in isolated locations. Each lab includes a Stratasys Fortus 250mc 3D printer, a computer numerical control milling machine, an array of fabrication tools, electrical diagnostic equipment, software programmes and global communications system. An example of use is development of metal covers for the Mine Resistant Ambush Protected vehicles to prevent damage from rocks or fixed objects to the valve system. The entire process from design to quick fabrication (with assistance from forward-deployed Research, Development and Engineering Command Field Assistance in Science and Technology Centre) took less than five weeks. Concurrent wheel redesign effort by the manufacturer was expected to take more than a year [217, 220].	TRL 9	3D printers and modelling software allow REF engineers to quickly design and validate a solution concept. The REF engineers work directly with the soldiers; they virtually design a prototype solution and print plastic mock ups for immediate testing and feedback. This ensures proper form, fit and function with the end user up front.	The labs still require reach-back support for guidance and oversight. Most solutions require three to five iterations before finalising the prototype. Currently used 3D printers only print in plastic polymers.
US Army: Using the Mobile Parts Hospital concept for instant fabrication of parts in a combat zone [217].	TRL 8-9	Reduced lead time for procuring spare parts.	
US Army: Medical Prototype Development Laboratory is part of the US Army Medical Materiel Development Activity. They are able to quickly design, fabricate and deliver prototypes of medical equipment to the field using 3D printers. An example product is a new lightweight litter stand that is collapsible and fits into a backpack. Another is prototypes of test kits such as the	TRL 7	The key benefits are in rapid development of more efficient solutions.	

Environmental Sentinel Biomonitor, which allows monitoring of water for toxic chemicals [220].			
DST Group, Australia: Two different AM processes have been demonstrated to restore aircraft parts: Supersonic Particle Deposition is used for non-critical, low risk components that are not in a heat affected area Laser Cladding is used for more critical, structural repairs on components in heat affected areas. Both methods allow for appropriate geometric restoration along with corrosion and wear protection [218].	TRL 8-9	Demonstrated cost-savings compared with traditional repair methods.	The processes have been tested on actual parts.
ETT Industries, NZ and UK: Trayser bike, which is the first of its kind to allow its users to 3D print replacements parts. The company has made .STL files for certain replacement parts available to its clients. The parts include rear mudguard and mudguard bracket, and front brake clip [362].	TRL 7	This may be considered one of the first steps towards consumer-end manufacturing in the commercial sector. The company emphasises the ability of the customers to personalise the bikes.	The parts currently listed are all non-structural, non-essential parts. As such, this example does not provide a test-case for the test and evaluation framework.
Hewlett-Packard: Now taking orders for its HP Jet Fusion printer which the company claims is 10x faster than existing machines and can manufacture parts at half the cost. The printers are roughly the size of two washing machines and start from US$130,000 for the 3200 series (US$200,000 for the 4200 series). The new feature in the printers is the ability to print electronics in the parts they create through use of conductive materials printed at the voxel level [221].	TRL 7	The company expects that this type of printer will enable mass production of parts through AM, rather than just rapid prototyping.	Printer cost.
MIT, US: "MultiFab" system that delivers resolution at 40 microns and is the first 3-D printer to use 3-D-scanning techniques from machine vision. It can self-calibrate and self-correct, and gives users the ability to embed complex components, such as circuits and sensors, directly onto the body of an object [222].	TRL 6-7	This specific solution can print with more materials simultaneously than any printer before it; can self-calibrate and self-correct; is cheaper than current state of the art printers by orders of magnitude - $7000 vs. $250000.	Speed for mass production remains an issue.
Picatinny Arsenal, US: Using an inkjet printer to print electronic components such as munitions antennas, fuse elements, and batteries. Inks that can conduct electric current, such as silver, are printed in layers onto film surfaces. For example, a radio antenna made of silver nanoparticles printed onto a flexible polyimide substrate could be embedded in a soldier's helmet. This may replace the antenna that currently attaches to the headgear [217].	TRL 5-6	This process may enable printing sensors directly onto a weapon or onto clothing. Generally, printed electronics use space more efficiently. Other applications may be in embedding strain gauges and other sensors to monitor performance and wear of various structures [217].	Practical applications yet to be tested.

Carbon3D, Canada: Continuous Liquid Interface Production (CLIP) is touted as the next generation 3D printing technology. The process is a photochemical process that bears resemblance to forming injection-molded parts. It works by projecting light through an oxygen-permeable window into a reservoir of UV-curable resin. The projected UV images solidify the part and the build platform rises. The process occurs in the 'dead zone' – the thin, liquid interface of uncured resin between a clear window into the resin tank and the printing part. Light passes through the dead zone, curing the resin above it to form the solid part. Resin below the curing part provides the continuous liquid interface that powers CLIP. The materials are novel polymers, including polyurethane and cyanate ester-based resins [227, 228].	TRL 7	The process is faster than traditional 3D printing. The parts have consistent and predictable mechanical properties and smoother finish. The company claims that unlike traditionally printed parts, which may have variable strength and mechanical properties depending on the direction of printing, CLIP parts behave consistently in all directions.	The company has only recently revealed their new technology and it is yet to be seen how they fare on the commercial market.
Twente University, Netherlands: A new contactless liquid deposition method for reliable printing at the 50-nanometer scale. Applications include printable electronics, printing scaffolds for cell research, arrays of DNA or proteins, photonic crystals, microfluidic structures, and MEMS structures for sensors [223].	TRL 5	Implications for many fields, including wearable electronics, health, and the efficacy/utility of a deployable additive manufacturing capability.	Enabling method developed; practical applications have not yet been tested.
Additive Manufacturing Next Generation Supergen Energy Storage Devices (government-sponsored project), UK: Developing a desktop printer to create batteries, supercapacitors and energy storage devices for phones or tablets, and solar, wind and wave power storage. They are analysing new techniques for rapid 3D printing with conductive graphene ink to create the batteries [224].	TRL 2-3	Potential for improved energy storage devices (so-called 'super' batteries, super- and ultra-capacitors) through incorporation of graphene ink and 3D printing of novel 3D shapes.	Research project has just started (runs for 3.5 years).
MIT, US: Glass 3D printer - ability to 3D-print optically transparent glass [178, 225, 364].	TRL 7	New materials can be printed.	Requires refined glass as feedstock, rather than e.g. desert sand.
WinSun, China: Used giant 3D printers to construct ten one-story houses in a single day with a combination of cement and construction waste. The printers were 33 feet wide and 22 feet high [10, 218].		This construction method is potentially faster, cheaper and safer than traditional methods.	Significant disruption to traditional building industry.
MX3D, Holland: Specialises in multi-axis 3D printing with use of robotic arms. This enables the manufacturer to 3D print both metals and resins mid-air, without the need for support structure. It also allows for a range of sizes, from bicycles to bridges. Students at the Technical University of Delft have demonstrated this technology by 3D-printing a stainless steel bicycle frame for their Arc Bicycle [229].	TRL 7		

MX3D, Holland: 3D printed a steel bridge across one of the city's canals using two modified multi-axis robotic arms [218].	TRL 7	Potential applications in bridging, HADR.	Requirement for the robotic arms; speed of construction.
Deloitte, 3D Systems and iSW Corp: Creating a parts-on-demand capability via a secure cloud environment that will house weapon system part designs [217].	TRL 7	More extensive data service.	Cyber-security concerns in military context.
Protective Materials			
US Army: Demonstrated rolls of lightweight sticky wallpaper lined with Kevlar fibres. The lining reduces the amount of debris flying at the occupants of a building in the event of an explosion [230].	TRL 4	Can be quickly and easily applied by non-specialised units at short notice.	Practical use yet to be tested.
North Carolina State University and the US Army Research, Development & Engineering Centre: Composite Metal Foam (CMF) armour. The foam is made of metallic hollow spheres made of carbon steel, stainless steel or titanium embedded in a metallic matrix made of steel, aluminium or metallic alloys. It is 25 mm thick with boron carbide ceramic strike face, Kevlar backing, and CMFs in the middle layer to absorb kinetic energy. In tests, it was demonstrated to stop a 7.62x63 mm M2 armour-piercing projectile with 8 mm indentation on impact (the US National Institute for Justice standard specifies 44 mm indentations) [231, 232].	TRL 4-5	For equivalent protection, CMF is lighter than metal plating; can withstand very high temperatures; thermally stable; shields x-rays, gamma rays and neutron radiation.	Two manufacturing techniques have been developed, but yet to be scaled up.
New York University and Deep Springs Technology: Demonstrated a new metal matrix composite (syntactic foam) that is light enough to float on water. It is made of magnesium alloy matrix composite reinforced with silicon carbide hollow particles and has a density of 0.92 grams per cubic meter. A single sphere's shell can withstand pressure of over 25,000 pounds per square inch (PSI) before it ruptures (100 times the maximum pressure in a fire hose). The hollow particles offer impact protection as each shell acts like an energy absorber during its fracture. The composite can be customised for density and other properties by adding more or fewer shells into the matrix [233].	TRL 4-5	A boat made of such composite will not sink even with structural damage. The material may also enable improvements in fuel efficiency for cars as it combines light weight with heat resistance. Amphibious vehicles such as those used by the military can especially benefit from the light weight and high buoyancy.	Yet to be tested within actual systems.
The Natick Soldier Research, Development and Engineering Centre (NSRDEC) and MIT, US: Developing 'second skin' – the next generation of chemical-biological protection for the war-fighter. The material design is based on responsive polymer gels such as organohydrogels and functional chemical species such as catalysts [234].	TRL 3-4	The skin is meant to be textile-based, lightweight, not retain heat, be air and moisture permeable and adapt to the environment. Contact with chemical and biological agents will trigger gel response to close the pores of the	Low TRL technology. Various components are being developed and integrated for testing.

		texture.	
DST Group, Australia: Researchers working with shear thickening fluids (STFs) have developed a new electrolyte that hardens upon impact. STFs are non-Newtonian fluids that move like a liquid until a force is applied to them in which case they harden in a few milliseconds [235].	TRL 4	Applications for defence include development of new types of body armour (such as the Liquid Body Armour from BAE), combat helmets, etc. DST Group researchers are looking at development of robust, high performance batteries with STF being used as electrolytes and providing intrinsic impact protection.	
University of Texas, US: Developed a ground-breaking new energy-absorbing structure to better withstand blunt and ballistic impact. The technology, called negative stiffness honeycombs, can be integrated into car bumpers, military and athletic helmets and other protective hardware [392].	TRL 5-6	Improved energy absorption and resilience. Primary applications are for better blunt and ballistic protection of soldiers, also in protection of goods/cargo being delivered by autonomous means, including precision air-drop.	Not yet tested against ballistic impact.
Smart Fabrics			
RMIT University, Australia: SkinSuit made of bi-directional elastics that is designed to mimic impact of gravity on the body and reduce the negative physical effects of space travel. The suit is currently being tested in at the International Space Station [393].	TRL 7	The suit design imposes a gradual increase in vertical load from shoulders to feet similarly to gravity.	Specific designs for space travel. Applications in defence context unclear.
Pentagon and MIT, US: An initiative to develop new textile and fabric technologies that would mix sensors into clothing to regulate temperature, detect biological threats, provide power or change colours. The consortium includes 89 manufacturers, universities and non-profit organisations [238].	TRL 3		Programme in early stages.
University of Exeter, UK: The first "truly electronic" textile has been created by pioneering a technique of embedding flexible graphene electrodes into textile fibres. Transparent and flexible electrodes have previously been used in glass and plastics, but this is the first example of them being truly embedded in a yarn [239].	TRL 4	Clear implications for wearable electronics – graphene exhibits flexibility, durability, strength, lightness of weight. The properties of the underlying textile remain more or less unchanged.	Still early days – applications of this new textile process not explored or exploited yet.
Cloaking Materials			
Iowa State University, US: Developed a flexible, stretchable and tunable 'meta-skin' that uses rows of small, liquid-metal devices to	TRL 4	Applications in EM frequency tuning, shielding and scattering suppression.	Low TRL technology. Future research aims to look at cloaking from higher

cloak an object from radar. The meta-skin is made of rows of split ring resonators filled with galinstan metal alloy, embedded inside layers of silicone sheets. The resonators are small rings that create electric inductors (the gaps between them create electric capacitors). Together, they form a resonator that traps and suppresses radar waves at certain frequencies [236].		Tests show 75% suppression in the frequency range of 8-10 gigahertz. The researchers claim that wrapping a platform in the skin would provide multi-directional suppression.	frequencies such as visible or infrared light.
Raytheon-UMass Lowell Research Institute, US: Developed printable inks for producing tunable EM filters for a variety of surfaces. These can be printed directly onto military equipment and serve as e.g. radio antenna or radar array or 'invisibility cloak'. The technology involves ferroelectric nano-ink, the properties of which can be tuned by an applied voltage printed directly onto sheets or the surface of objects [237].	TRL 4	Can potentially be used to create an anti-radar 'invisibility cloak' for military vehicles by redirecting radar waves away from sender and adapting to changing circumstances. Expected to have the flexibility to tune to whatever frequency the enemy radar is operating at, giving a wider range of protection against different radar systems.	Low TRL technology. Practical usefulness yet to be demonstrated.
Structural Materials			
UNSW, Australia: Used the Australian Synchrotron to develop new high-strength, ultra-low density, corrosion-resistant magnesium-lithium alloy. The alloy forms a protective layer of carbon-rich film when exposed to air and this protects it from corrosion. This makes it the first magnesium-lithium alloy to stop corrosion from irreversibly eating into the alloy [240].	TRL 4	The alloy weighs half as much as aluminium and is 30% lighter than magnesium. This can give better fuel efficiency to ground and air platforms.	Cost-effective mass production and consistent properties on a large scale are yet to be demonstrated.
University of Trento, Italy: Spider silk matches high-grade alloy steel for tensile strength but is about a sixth as dense. It is also highly ductile, sometimes capable of stretching to five times its length. Researchers also fed (sprayed with a solution of) carbon nanotubes to spiders to produce silk that is even stronger – reinforced by those carbon nanotubes. This material has properties, such as fracture strength, Young's modulus and toughness modulus higher than any fibre ever measured, including Kevlar fibres [242].	TRL 4	Harder, stronger, lighter materials for just about anything amenable to fibres (e.g. armour, clothing). Applications even extend to tissue repair. The simple technique could also be applied to other plants and materials – this is being explored.	Still unsure as to how this process works (e.g. they believe it unlikely that the silk is simply coated with the carbon nanotubes after it is spun, but rather is ingested). There's still no efficient way to harvest spider silk on an industrial scale.
UT Dallas, US: Created new structures that exploit the electromechanical properties of specific nanofibers to stretch to up to seven times their length, while remaining tougher than Kevlar. These fibres utilise the electromechanical properties (through piezoelectric effects) to reinforce themselves [241].	TRL 3-4	Proof of concept showed that these fibres can absorb more energy before failure than the materials conventionally used in bulletproof armour.	Low TRL technology
Adhesives			
University of California, US: Improved upon a small molecule called	TRL 4-5	There is real need in a lot of	Early days in the development, which

the siderophore cyclic trichrysobactin (CTC) that they had previously discovered. They modified the molecule and then tested its adhesive strength in aqueous environments. The result is a compound that rivals the staying power of mussel glue [243].		environments, including medicine, to be able to have glues that would work in an aqueous environment.	has thus far focussed on the molecular dynamics required for adhesion in aqueous environments.
Nanyang Technological University, Singapore: Electric glue that starts bonding when a small voltage is applied across it and stops when voltage is removed. Can set "anywhere" provided a voltage can be applied, as it doesn't rely on chemical means, or chemical changes induced by heat or light, to harden [244]. For example, it can glue metal panels together underwater.	TRL 5	Significant implications for maintenance (bolts, screws, temporarily fixing cracks etc.), or even soldier health (although it isn't particularly flexible).	Action of the glue is not reversible, yet. (Not necessarily a problem, depending on the circumstances).
DST Group, Australia: The Signatures, Materials and Energy Strategic Research Initiative is developing technology for embedding antennas into vehicle outer skins by sewing conductive textile threads into plies of uncured composite. The plies are then laid in a mould and cured in an autoclave. The threads are then soldered to a traditional radiofrequency connector. The 3D array of conducting threads in the non-conducting composite becomes a metamaterial where the conductors interact with the electrical fields in RF waves.	TRL 4	Appropriate distribution of the conductors enables same response in the metamaterials as that in a traditional antenna that is six times larger.	At this stage, only moderate performance has been achieved with use of off-the-shelf uncured composites.
Shape-shifting and Biodegradable Materials			
Georgia Institute of Technology and the Singapore University of Technology and Design: Developed 3D structures that sequentially fold themselves from components that are flat or rolled into a tube for shipment. The components respond to stimuli such as temperature, moisture or light with smart shape memory polymers (SMPs) changing shape in a controlled sequence over time [245].	TRL 3	Infrastructure and equipment may be transportable in a much smaller space taking up fewer transportation platforms. This may also be useful in HADR situations. Other potential applications include UAS that change shape depending on requirements.	Low TRL research; practical applications are yet to be demonstrated.
US Army: Funding 4D printing research at Harvard University, University of Pittsburgh, and University of Illinois. The research projects look at how self-assembling objects can be used to make tactical bridges, shelters and other equipment [10].			
Harvard University, US: Material made from tiny cubes which can fold down flat or pop-up to create stiff, three-dimensional walls. The structure can also change depending on need [246].	TRL 4	The researchers see applications in rapid shelter construction (e.g. for camping).	Low TRL technology; practical applications yet to be tested.
University of Wollongong, Australia: Experimenting with 4D printing by creating objects that change shape over time. One such object is a valve that opens and contracts under the influence of water	TRL 5	The authors suggest application to Army battlefields, where a lot of electronics is left behind – and if 3D-	Still some way to go between the valve and such disappearing electronics. Note also that this behaviour does not

and temperature. No power source or programming required. This is the first time four different hydrogel materials have been used in concert to create such an object [247].		printed electronics can be created that undergo transient behaviour (e.g. dissolve) if they get too hot, cold, wet etc., they could completely disappear once armed forces leave.	necessarily require '4D' printing.
University of Wisconsin, US: Made electronic components on the surface of a rigid wafer made of a semiconducting material, but then used a rubber stamp to lift them from the wafer and transfer them to a new supporting surface made of nanocellulose without reducing performance. They also showed that these chips can be broken down by a common fungus [248].	TRL 5	Less raw material used; cheaper; improved environmental outcomes. Opens the way for so-called "transient electronics" - disposable, biodegradable electronics for such things as swarms of cheap, biodegradable UAS and other platforms.	It may take heightened environmental pressure or a spike in the price of rare semiconductor materials like gallium, for the mainstream electronics industry to change its current practices and consider making chips from wood.
University of Illinois: Developed heat-triggered self-destructing electronic devices that utilise acid trapped by wax. A 'self-destruct' signal initiates a small heating element that melts the wax, releases the acid, and dissolves the circuitry [249].	TRL 6	Military applications in electronics disposal; has second-order implications for environmental concerns/waste management.	More testing required for practical use.
Self-healing Materials			
UT Austin, Texas State University, US: A new hybrid gel composed of conductive polymer and a metal-ligand supramolecule. It has high conductivity, appealing mechanical and electrical self-healing property without any external stimuli, works well at room temperature, and enhanced mechanical strength and flexibility [250].	TRL 5	Improvements to existing self-healing materials. Improved mending ability in the field, particularly useful for unmanned, remotely operated and/or autonomous platforms or equipment.	Practical applications not yet tested.
Vrije Universiteit Brussel, Belgium: Self-healing actuators based on a mechanical fuse that breaks first when the system is subjected to forces/stresses that are beyond what it can handle, but which can 'reset' (healed). The material used is a Diels Alder polymer that can 'heal' at relatively low temperatures (70-130 degrees Celsius) and be as strong after the fracture as before [251].	TRL 4	Mechanical strength of the fuse can be adjusted. May reduce the need to over-engineer robots, reducing complexity, weight and power requirements as well as cost.	Early prototypes only. Cannot yet be healed in-situ. Broader application areas, including heavier-duty applications, need to be explored.
University of Alicante, Spain: A flexible polymeric material (transparent resin) that can self-heal and has shape memory properties. It can heal in air or in fluids. When cut in two, it can re-join within 10-15 seconds without any external trigger or energy source. It is also biocompatible, due to a lack of chemical reaction [252].	TRL 4-5	Has potential application in many fields, from manufacture to robotics and autonomous systems to medicine (e.g. internal catheters) to maintenance of equipment.	Practical applications yet to be tested.
Water Generation			
WaterGen, Israel: Selected by the French Army to equip their new armoured infantry fighting vehicles with the GEN40V atmospheric	TRL 8-9	The system utilises minimum space in the vehicle, effectively replacing the	

generators or Water Treatment Units (designed to extract water from the vehicle's air-conditioning systems). It produces 30-75 litres/day depending on environmental conditions. WaterGen is already supplying similar solutions to the IDF Merkava Mk4 and Namer armoured infantry vehicles [253].		weight of water that would otherwise be carried. It enables independent water generation that meets required quality standards. Easy to operate and maintain.	
Desolenator, UK: Low-cost portable desalination technology powered by solar. The Desolenator can desalinate up to 15L of water per day and costs around $450. It is expected to operate for up to 20 years [10, 254].	TRL 7	Low cost; robustness; use of renewable energy source. Suitable for maritime operations.	The company is looking for funding to commercialise the product.
pAge Drinking Paper, US: A book comprised of pages embedded with silver nanoparticles. Printed on each page is information on water safety both in English and the language spoken by those living where the filter is to be used. Each page can be removed from the book and slid into a special holding device in which water is poured through and filtered. A page can clean up to 26 gallons (100 litres) of drinking water; a book can filter one person's water needs for four years. The product has been tested on sewage-contaminated water in Africa, achieving 99.9% purity [255].	TRL 7	New purification technique for in-situ water generation/scavenging to reduce log burden by reducing demand for transport of potable water.	Ability to scale up the product (from a " lab bench experiment to a manufactured product.")

Appendix E Horizon Scan of Sensors

Examples	TRL	Applications and Benefits	Challenges and Barriers
Internet of Things			
Hamburg, Germany: 'SmartPort' project saw sensors embedded in everything from container handling systems to streetlights and improves cargo handling efficiency and predicts environmental impacts through sensors for noise and air pollution [256].	TRL 7-8	Efficiency, continuous operations, positive environmental effects.	Cyber-security; data management; protocol standardisation.
China: Leading the world in adoption of machine-to-machine (M2M) services with 74 million connections at the end of 2014 (representing almost a third of the global base) with support of the leading mobile operators: China Mobile, China Telecom and China Unicom [257].	TRL 7	Benefiting from government support, economies of scale and partnership between companies from different sectors as well as increasing standardisation.	May be harder to establish in less directive states.
Biometrics			
American Institute of Physics: An advanced fingerprint scanner that not only captures a 3D image of a fingerprint, but also the tissue below it. This is done by what is essentially a tiny ultrasound imager [258].	TRL 6-7	More robust and secure fingerprint identification. Other applications are in (e.g.) weapons coded to user. The ultrasound aspects have a medical application in diagnostics.	Integration of biometrics into Defence applications; not yet commercialised.
Carnegie Mellon University, US: Demonstrated iris recognition technology that works from up to 12 m. Non-contact identification from a significant distance away [259].	TRL 5-6	Improved security and convenience; replacing passwords.	Legal issues; social tensions around surveillance; data security; accuracy.
Laser Sensors			
Quanergy, US: Developed solid-state light detection and ranging (LIDAR) sensor for advanced driver assist systems and for self-driving cars. The sensor has no moving parts but can scan in every direction on both macro and micro scales [260].	TRL 4-5	The applications for transportation are in local situational awareness, driver assisted movement, terrain mapping, and intelligence analysis. When commercialised, the system is expected to cost under US $1000 per car.	Not yet commercialised.
DARPA, US: Demonstrated a LIDAR-on-a-chip device "Short-range Wide-field-of-view Extremely agile Electronically steered Photonic Emitter", or "Sweeper". By sweeping using a phased array mechanism similar to modern RADAR, it is able to sweep across its range 100,000 times a second - 10,000 times faster than today's best (mechanically rotating) LIDAR [261, 262].	TRL 4-5	Improved ability for machines (e.g. autonomous vehicles) to navigate more precisely and accurately through improved perception of the environment. Much faster than conventional LIDAR, and can be	Covers only a 51-degree field of view (rather than the full 360 degrees of a rotating device) but increased speed and input from numerous sensors around a vehicle can easily be stitched together into a panorama.

		hidden.	
Spectroscopy			
Tsinghua University, China & MIT, US: First spectrometer using quantum dots with an array of 195 different types of quantum dots with absorption spectral features that cover a wavelength range of 300 nm, dispersed in solution as colloids, then used to coat individual pixels of the light-detecting array of a digital camera. Rather than e.g. using a prism to bend light into constituent wavelengths, the quantum dots create an array of band-pass filters for light to pass through before it reaches a position-sensitive detector [394].	TRL 4	Compatible with existing camera technology, meaning the spectrometer could be mass-produced at a relatively low cost. Wide range of applications, from gathering scientific data on space missions to sensors integrated within household appliances.	Still a stand-alone technology demonstration, not yet integrated into sensors. Device architecture still needs optimisation.
University of Adelaide, Australia: Developed an instrument that uses an optical frequency comb that sends up to a million different light frequencies through a gas sample in parallel to measure the molecular content of the sample. They use optical spectroscopy to detect the light-absorption patterns of different molecules, with high levels of accuracy and speed. Targeted at breath analysis for detection of disease, the device has high sensitivity, has results available almost instantly, and can test for a range of molecules all at once [395].	TRL 4	Improved diagnosis capability, for more accurate and earlier diagnosis of many diseases, including various cancers, asthma and diabetes.	Working prototype anticipated within 2-3 years. Still need to determine how to accurately sample and interpret molecule levels that will naturally vary from person to person.
Chemical Biological Radiological Nuclear (CBRN) Detection			
DST Group, Australia: Developed the Black Canary device which constantly samples air into a series of detection cartridges in order to provide immediate warning of CBRN threats to users. Each cartridge is a miniature chemical spectrometer which is combined with a base electronics unit and can self-calibrate [268].	TRL 5-6	The device is coupled with the capability to transmit data wirelessly to a range of other devices. It is suited for military, first responder, and mining/industrial applications.	The project is currently seeking industry partners for further development.
Canadian Armed Forces (CAF): Use Multi-Agent Tactical Sentry (MATS) UGS for CBRN reconnaissance and detection. It is tele-operated, has integrated CBRN sensors, a heavy-duty manipulator arm, zoom camera and GPS waypoint following. Weight is 815 kg [263].	TRL 9		
Qinetiq's Talon and iRobot's Packbot also have CBRN reconnaissance capabilities [15].	TRL 9		
CAF: Use unattended ground sensors such as Vital Point Biological Agent Detection, Sampling and Identification (VP Bio Sentry) for CBRN detection [264].	TRL 9		
Northwestern University, US: Developed a custom-tailored, compact	TRL 4-5	Applications include sensing of	Yet to be demonstrated in practical

laser diode by integrating multiple wavelength emitters into a single device. Nearly all chemicals, including explosives, industrial, and pollutants, strongly absorb light in the mid-infrared wavelength region, which is often called the "fingerprint region" for chemicals. Until now, lasers that work within this range had significant limitations. Larger, optically pumped lasers are too complex to use out in the field, and compact, lightweight diode laser sources have a limited spectral range. The new laser device is smaller than a penny and works at room temperature. It can also emit light at frequencies within +/- 30 percent of the laser central frequency, which has never before been demonstrated in a single-laser diode [265].		explosive threats, diagnosis of serious illnesses (from breath). Overcomes limitations of existing mid-infrared lasers (size, limited spectral range).	applications.
George Washington University, US: New technology that can detect traces of chemicals at concentrations of 10^-19 moles. The technology is called REDIchip (Resonance-Enhanced Desorption Ionization) [266]. Originally developed to help identify potential chemical and biological threats, but has application in many other areas including health [267]. Partially DARPA-funded.	TRL 8-9	Reduces the time required to identify biological and chemical matter, with improved sensitivity. Potential applications include identification of chemical and biological threats, detection of drugs in urinalyses, earlier detection of emerging health problems, enhanced medical imaging, improved tumour margin determinations and identification of endocrine disruptors in the environment.	Not all practical applications have been demonstrated.
GPS-Independent Navigation			
US DoD Communications Electronics Research Development and Engineering Centre (CERDEC): Developing the Warfighter Integrated Navigation System (WINS) that can track soldier movements without GPS, and provide 'precise' geolocation information despite no GPS. It uses Inertial Navigation Systems (INS) sensors similar to those in a smartphone, but more accurate [269].	TRL 5	Asset and human tracking; improved situational awareness; potential medical applications with use of pedometer and accelerometer.	If based purely on INS, there is an upper bound to how accurate the "precise" information will be, and the inaccuracy grows with time unless location can be 'synchronised' at regular intervals.
DARPA, US: Micro-PNT program is developing high-performance miniature inertial sensors to enable self-contained inertial navigation for precise guidance. This includes sensors that operate under high dynamics and sensors that self-calibrate, as well as fully integrated miniature timing and inertial measurement units and miniature atom-based inertial sensors for extended operation [270].	TRL 4-5		
Condition Monitoring			
US RDECOM Logistics Research and Engineering Directorate Future	TRL 5	Expected benefits include improved	

Concepts Division (LRED-FCD): Developing Remote Readiness Asset Prognostic/Diagnostic System (RRAPDS): an integrated sensor suite to monitor temperature, humidity, 3-axis shock and vibration and store all data on board the device throughout the lifecycle. The product is a multi-sensor device with 9 year battery life, shock sensing capability up to 9000 Gs, RF capability for remote wireless data collection, and ability to program and execute diagnostic algorithms on-board [151].		safety and reliability, continuous product improvements, and reduced requirement for stockpiling, reliability testing and cost.	
LRED-FCD: Developing an Embedded Propellant Analyzer (EPA) with capability for continuous real-time stability monitoring of propellant assets at the depot and/or field level. They are further looking to use handheld Raman spectroscopy devices for propellant monitoring (such as the Thermo Scientific TruScan device) [151].	TRL 5-6	Expected benefits are to reduce test costs by more than 80% and introduce continuous real-time monitoring at the depot level. Raman spectroscopy devices enable onsite surveillance of broader range of propellants [151].	
University of Warwick, UK: 'Q-Eye' sensor that senses radiation in the Terahertz region of the spectrum. It detects the rise in temperature produced when the EM radiation emitted by an object is absorbed by the Q-Eye sensor, even down to the level of very small packets of quantum energy [271].	TRL 5	Non-destructive monitoring and testing, including for quality control in pharmaceuticals or food, and for medical diagnosis; may be useful in astronomical and climate science observations. Cheaper, more sensitive, and quicker than existing sensors of this type.	Prototype only, demonstrators to be developed over the next couple of years.

Appendix F Horizon Scan of Information and Communication Technology

Examples	TRL	Applications and Benefits	Challenges and Barriers
Quantum Computing			
Centre for Quantum Computer and Communication Technology (CQC2T), Australia: Focus on use of single donors in silicon for creation of quantum computers. At this stage, researchers have two quantum bits and aim to have ten by 2018 [273].	TRL 3	Despite only having two qubits operating, the technology has attributes that make it scalable and more compatible with current computing technologies.	Single donors in silicon is a very challenging way to make a quantum computer as extremely high precision is required to place atoms within silicon to act as individual quantum bits.
MIT, US: Developed a quantum computer from five atoms in an ion trap with lasers pulses used to carry out Shor's algorithm on each atom to correctly factor the number 15. The system is designed so that more atoms and lasers can be added to build a bigger and faster quantum computer. Each of the five atoms can be held in a superposition of two different energy states simultaneously. Laser pulses are used to perform 'logic gates' (components of Shor's algorithm) on four of the five atoms. The results are then stored, forwarded, extracted, and recycled via the fifth atom. The system is held stable with use of an ion trap, where the atoms were charged by removing an electron from each atom and the atoms were held in place with an electric field [272].	TRL 3	The first quantum computer based on one molecule was built in 2001 but was not scalable. Once more atoms were added, the system became more difficult to control. The current development is for a more efficient and scalable system.	An actual quantum computer would still take a lot of money to build and require a considerable engineering effort. The researchers suggest that encryption that relies on factoring as a hard-to-invert problem may become obsolete once these systems are available [272].
Swinburne University of Technology, Australia: Created entangled photon states with unprecedented complexity and over many parallel channels simultaneously on an integrated chip. The researchers used 'optical frequency combs' to 'tangle' the photons [274].	TRL 3	The chip was created using processes compatible with current computer chip industry, which makes it easier to incorporate them directly into laptops and cell phones.	Enabling technology at proof-of-concept level. Functional chips have not yet been created.
NASA Jet Propulsion Laboratory, US: Successfully teleported information about the quantum state of photon over 15 miles of optical fibre. This quantum teleportation is a key component of quantum computing networks [10].	TRL 3		
Eindhoven University of Technology, Netherlands: Demonstrated a nanoscale device that can 'sculpt' individual light photons on demand. Precise control of photon flow is expected to be a key technology for developing secure quantum networks [10].	TRL 3		

Neuromorphic Computing			
Cornell University, US: Neuromorphic computing system designed for energy-efficient evaluation of large-scale neural networks. It consists of a non-conventional compiler, a neuromorphic architecture, and a space-efficient microarchitecture that leverages existing integrated circuit design methodologies [275].	TRL 6	Improvements in power requirements and execution speed of neural networks.	This particular methodology requires burning circuits into a Field Programmable Gate Array (FPGA), to provide what is essentially custom hardware.
Innovation Centre of Western Australia: Developed a hardware chip that has the ability to learn autonomously, evolve and associate information and respond to stimuli like a brain. It could be used in applications including robotics, voice recognition, driverless cars, drones and smartphones. This is a hardware-only solution, so execution is much faster than for multi-purpose programmable hardware that executes software (claims of 5000 times faster, using 1/1000 of the power) [276].	TRL 7	Primary applications in 'learning' in a similar way to a neural network. The company claims to be 10 years ahead of everyone else, including IBM (i.e. Synapse program, and the TrueNorth chip that is hardware designed specifically to function as a neural network, but which is programmed using software).	Not applicable to everything, only to systems that 'learn' in the way of neural networks and other AI learning techniques.
AI			
Alphabet, US: In 2011 Demis Hassabis founded DeepMind company, seeking to transfer biological intelligence knowledge to machines. The company developed software that learned to play Atari games in 2013. Google purchased the company in 2014 and expanded its research base. In January 2016, it revealed existence of AlphaGo, which beat the world champion at Go in March 2016. The company aims to create general artificial intelligence that can learn to take on any task. The programme uses reinforcement learning, loosely based on the way animals are taught new tricks with rewards and punishments. The software is programmed to explore its environment and adjust behaviour to increase some kind of virtual reward. It also uses system for evaluation of possible moves and a search mechanism for selecting the most promising moves. This is combined with the 'deep learning' method that has recently delivered advances in ability to decode information such as images [277].	TRL 4-5	The future vision is application in diverse tasks such as advancing medicine by formulating and testing scientific theories, or bounding around in agile robot bodies that are better able to deal with the world. DeepMind is currently working with the UK National Health Service on a project that aims to train software to help spot signs of kidney problems; these cause a large number of avoidable deaths. They are also working with business divisions of Google, where the technology may be used as virtual assistants or for improving recommendation systems for products such as YouTube.	Concerns have been raised by prominent thought leaders such as Stephen Hawkins and Elon Musk on the dangers presented by AIs. One of critical challenges is the chunking process that human and animal brains use to deal with complexities. Hassabis identifies this as one of the most core problems left in AI. Additionally, some experts are sceptical about the long-term potential of reinforcement learning approach.
Apple: Viv – the new generation virtual assistant that supersedes Siri is a form of AI can determine the intent of a question and can write its own program in order to answer it. Apple is looking to	TRL 5-6	Dynamic programming offers new capabilities as does ability to chat with devices in a natural language.	The system is still in development and doesn't yet have a voice

incorporate AI into every device such as iPhones [278].			
IBM: Plans to add new AI techniques, including deep learning, to the commercial version of Watson. This could make the platform considerably smarter and more useful, and points to a new direction for AI research. Combining disparate strands of AI research could become an important trend in coming years [279].	TRL 6	Potential improvements to data analytics and machine learning, including logistics supply chain operation, demand forecasting, planning and scheduling.	Although the results produced by deep learning systems are often spectacular, the systems responses are extremely specialized and they can fail in surprising ways because they do not comprehend the world in a very meaningful way.
University of Cincinnati, US: Developed AI called ALPHA which was recently tested by experienced fighter pilots and comprehensively defeated them in a high-fidelity air combat simulator. The AI was able to consistently defeat the human experts even when deliberately handicapped in terms of speed, turning, missile capability and sensors. The computing power required for the AI is equivalent to that of a low-budget PC. This is achieved with use of language-based control and the Genetic Fuzzy Tree (GFT) system (a subtype of fuzzy logic algorithms). The researchers describe the approach to programming as 'language based, genetic and generational' [281].	TRL 5-6	For military setting, it presents an opportunity to gain tactical advantage over the enemy in combat situations. The speed of the AI means that it can consider and coordinate the best tactical plan and precise responses in a dynamic environment much faster than human opponents. The researchers are looking to develop it into a 'teammate' for air operations [281].	This type of system also presents a potential threat if an arms race results in AIs controlling tactical decisions. One risk is start of flash wars due to decisions being made too fast for humans to control. The researchers intend to continue developing ALPHA to increase fidelity of aerodynamic and sensor models.
Narrative Science: AI system Quill analyses raw data and generates natural language. It can produce reports that look like they were written by human authors in matter of seconds [11].	TRL 7		
Alphabet, Google: Developing a new system of pedestrian detection that relies on simple video (computer vision and machine learning), rather than radar, LIDAR, etc. This method uses deep neural networks, but applies them in a three-step process, essentially inserting an initial screening/filtering process to reduce the amount of the video image that requires the deep (and time-expensive) processing [280].	TRL 8	Useful in convoys or any application of autonomous (self-driving) vehicles around people or dynamic obstacles. Cheaper, and provides an additional protection measure on top of existing systems if used in conjunction with the existing systems.	Slower to process video data when compared to radar, LIDAR etc., but with use of deep neural networks time has been reduced between 60 and 100 times, down to 0.25 seconds (still not as low as the 0.07 seconds that Google desires).
Data Storage			
Harvard Medical School & Technicolor, US: Reduced a digital file into binary and then matched that binary to DNA bases. Researchers were able to encode 10 megabytes to a DNA sequence and then decode it later within several hours [282].	TRL 3-4	Applications in storing large quantities of media for archival purposes. DNA can fit petabytes of information in a drop of liquid and survive for more than 100,000 years in the right conditions.	Low TRL. Currently, the biggest limitation is time. It takes days to encode 10 MB and about eight hours to decode.
Institut Charles Sadro & Aix-Marsellie Universite, France: Built	TRL 2-3	Currently, storing one zettabyte (1	Low TRL. Research has been ongoing

binary data into a strand of synthetic polymer. The scientists assigned chemical components (monomers) to represent zeros and ones. To build the polymer, the monomers are strung together in a specific order and a mass spectrometer is used to read the data [282].		billion terabytes) would take roughly 1000 kg of cobalt alloy. If proven successful, use of synthesized polymers would reduce this to 10g. This may be an alternative to DNA for storing data.	for two years and scientists were able to chain a handful of bytes of information together. They hope to progress to kilobytes in the next five years.
Researchers have used a programmable DNA 'processor' to determine the shortest route between two starting points and two destinations in a 6-location network with multiple paths between locations. This work builds on previous work showing storage and processing of information with the genetic material and performing basic computing tasks [396].	TRL 4	DNA has attractive properties in terms of its programmability, fast processing speeds and small size. This work may eventually lead to an alternative to silicon-based processing and the impending 'end of Moore's Law'.	A long way to go yet to be competitive in a practical/pragmatic sense with conventional computer processors/processing.
ETH Zurich, Switzerland: Encoded DNA with 83 kilobytes of text. The researchers encapsulated the DNA in silica spheres and warmed it to nearly 160 degrees Fahrenheit for one week, which is the equivalent of keeping it for 2,000 years at about 50 degrees. When they decoded it, it was error-free [283].	TRL 5-6	Size and durability: DNA offers massive data storage capabilities, with similarly massive longevity advantages over conventional digital techniques.	Searchability: there is currently no way to label specific pieces of information on DNA strands to make them searchable - this is the next research problem being tackled.
Intel & Micron: 3D XPoint™ technology is a non-volatile (permanent) memory that benefits any device, application or service that benefits from fast access to large sets of data. Now in production, 3D XPoint technology represents a major breakthrough in memory process technology and the first new memory category since the introduction of NAND flash in 1989 [397, 398].	TRL 6-7	1,000 times faster and has up to 1,000 times greater endurance than NAND (used in most solid-state storage), and is 10 times denser than conventional memory. Much faster access to large sets of data - particularly useful for "big" data analytics (e.g. fraud detection) healthcare (e.g. genetic analysis), machine learning, even high-resolution gaming.	Not yet mainstream technology.
Data Security			
Queensland University of Technology, Australia: Developed and tested a new quantum-proof version of Transport Layer Security (TLS) Internet encryption protocol that incorporates a mathematical technique called the 'ring learning with errors problem', a fairly recent technique that mathematicians think has the potential to resist quantum attacks [284].	TRL 6	The researchers believe their algorithm to be quantum-computer-proof.	Algorithm is slower than conventional Transport Layer Security, and work is needed to speed it up.
Ruhr-Universitat Bochum, Germany: Developed "PHYSEC," a technology based on a random number generator that grants two parties access to a synchronised sequence of random numbers. The	TRL 7	Better security of wireless transmissions; avoids the problem of a security key shared by all devices.	Needs to be proven in a tough environment against determined hackers.

keys are only shared by pairs of communication partners and not by all devices within the network. A mobile phone app will be available to include the new devices into an already existing "Net of Things" secured by "PHYSEC" [399].			
MIT, US: Developed a new system called CodePhage that repairs dangerous software bugs by automatically importing functionality from other, more secure applications. It doesn't require access to the source code of the applications whose functionality it is borrowing. Instead, it analyses the applications' execution and characterizes the types of security checks they perform. As a consequence, it can import checks from applications written in programming languages other than the one in which the program it is repairing was written [285].	TRL 6-7	Reduction in the time and effort spent by software developers in performing security checks (80% of code in commercial software relates to this), through automation of the insertion of appropriate checks.	The bug-fixing software itself is open to cyber-attack and subversion.
Data Transmission			
Facebook: Built its first full-scale solar-powered drone (high-altitude pseudo-satellite, HAPS) designed to provide internet access to remote areas. The Aquila drone has wingspan similar to Boeing 737 (42 m), weighs about 400 kg, and is designed to hover between 18,000 metres and 27,000 metres (above altitude of commercial planes and above weather). It is expected to be able to fly for 90 days at a time. Facebook has also just completed testing of a new laser, as part of a laser communication system, capable of transmitting 10 gigabits per second, an can connect to a point the size of a small coin from 10 miles (16 km) away [286-289].	TRL 5-6	The company produced the drones in order to expand internet access across the world. Similar concepts can be used to enable localised military communications networks and persistent surveillance.	Some legal hurdles are yet to be overcome. Effectiveness of the system is yet to be demonstrated in practice. Details of the conditions under which the laser communication system speed and accuracy claims were made are not specified.
UK MoD: Acquired Zephyr solar-powered UAS designed to keep flying for months at a time. The UAS were originally developed by QinetiQ and are now owned by the Airbus Group. The current model, Zephyr-8 has wingspan of 25 m; it has 40% of its total 60 kg mass dedicated to energy storage; and can carry up to 5 kg payload, i.e. enough for a powerful camera system or similar equipment. In test flights above 65,000ft, HD video with 50 cm resolution has been streamed in real-time. In demonstrations, Zephyr was shown to be able to operate at any time of the year up to about 40 degrees North and South of the equator [290].	TRL 7-8	The system's unique advantage over other UAS is persistence. A HAPS can maintain constant vigil over a particular spot for months at a time (unlike satellites which some overhead only once every 90 minutes). Defence applications would primarily involve ISR, but may also be in providing mobile communications.	Use in military operations yet to be demonstrated.
Airbus: Contracted by OneWeb to build the world's largest satellite constellation. The company will produce 900 spacecraft in order to	TRL 2	Ubiquitous connectivity. The multi-billion-dollar OneWeb constellation	OneWeb will have to raise hundreds of millions of dollars to maintain a

broaden internet access. The plan envisages 20 planes of satellites in the sky connecting to small user terminals on the ground. These terminals would then link out to local phone networks and web hubs. More than 600 satellites will initially be launched, with the rest held as spares [291].		will dwarf any previous commercial network in the sky by a factor of 10.	venture that will not be fully operational for some years. No launches envisioned before 2018.
NASA: Developing small satellites (CubeSats) for ubiquitous communications, with preparations to launch and test a set of miniature satellites to explore space-to-Earth communications and satellites flying in close formation [292].	TRL 6-7	Exploring the barriers to using such satellite systems for ubiquitous connectivity.	
US Army: Space and Missile Defense Command-Tech Centre (SMDC) have developed and tested a nanosatellite that provides voice and data. They are also developing an imaging satellite. The first SMDC-ONE satellite is already in orbit, and three others were planned for later in 2015 and more in 2016 [293].	TRL 7	"a cellphone tower in space, except … it's for Army radios". The satellite can connect dismounted soldiers to a base or to sensors in the area.	The planned imaging satellites can only process one image at a time, requiring prioritisation of tasks. The ground resolution in 2-3 metres.
Oledcomm, France: Demonstrated Li-Fi technology within a smartphone that is placed under an office lamp. The technology uses the frequencies generated by LED bulbs (which flicker on and off imperceptibly thousands of times a second) to beam information through the air, like a digital Morse Code. The bulbs are fitted with a microchip, which turns them into a Li-Fi hotspot. Apple is looking at integrating the technology into their smartphones [294].	TRL 6	The key advantage of Li-Fi is speed, with theoretical speeds of over 200gbps shown in laboratory tests. This is 100 times faster than Wi-Fi which uses radio waves to transmit data.	Not yet commercialised. The technology only works if the device is placed directly in the light; it cannot travel through walls. (Although this may work well in places where Wi-Fi is likely to be restricted, such as schools and hospitals, and will increase privacy.)
City College of New York, US: Novel polarisation of laser light to increase the bandwidth of laser-based communications. In principle, the number of possible polarisation 'shapes' is unlimited, and could scale the amount of data being transmitted by a single laser beam [295].	TRL 5	Increases in bandwidth.	Adoption of light-based communications has security implications within military environments.
IBM: Designed and tested a fully integrated wavelength multiplexed silicon photonics chip, which will soon enable manufacturing of 100 Gb/s optical transceivers [297].	TRL 4-5	This will allow data centres to offer greater data rates and bandwidth for cloud computing, big data applications, and bulk data transfer.	Not yet commercialised.
University of Utah, US: Optical communications on a nano-scale using optical interconnects instead of electrical (e.g. copper) ones for chip-to-chip communications has been shown to reduce power consumption by 95% and increase bandwidth tenfold [296]. The	TRL 3-4	Significant implications for power and energy, for hand-held electronics through to large data processing centres.	Low TRL research.

researchers developed an ultra-compact beam-splitter for this purpose [400]. Further, Stanford University researchers have developed an 'inverse' design algorithm for producing designs for such beam-splitters based on a statement of the desired function/purpose [401].			
University of Twenty, Netherlands: Advances in photonic chips for communication with light – embedding 'active' properties in the chips including generating, strengthening and modulating light. The photonic chips developed do all this with the widest frequency range ever achieved [402].	TRL 4	Faster communications	Relatively low TRL research. Adoption of light-based communications has security implications within military environments.
University of Virginia, US: Devised a way of using light waves from light-emitting diode fixtures to carry signals to wireless devices at 300 megabits per second from each light. They developed a modulation algorithm that increases the throughput of data in visible light communications. More data is transmitted without using any additional energy [403].	TRL 7-8	Potential for high-speed comms utilising existing LED lights with more access points than Wi-Fi. Potential for more secure communications confined to a closed room; can be used in places where radio waves may be a problem (e.g. hospitals, aeroplanes)	Potential for less secure communications, e.g. ability to monitor and interpret light over great distances.
Interfaces			
Melbourne Royal Hospital, Australia: Developed a 'stentrode' the size of a paperclip that sits inside a blood vessel next to the brain. It records brain activity and converts the signals to electrical commands to move bionic limbs, remaining in place for months at a time. The research is sponsored by DARPA and represents a proof-of-concept for the 'brain modem' [302, 303].	TRL 4	The researchers have conducted tests that demonstrate control of bionic limbs and intend to implant the stentrode in a small group of spinal cord patients next year. The device also demonstrates the validity of this method for control of electric systems.	All stents entail a risk of causing blood clots and strokes (although injecting the stent into a vein minimises the risk). It is still not known whether the stentrode can record the kind of fine data that DARPA seeks to handle [302].
DARPA, US: Ground X-Vehicle Technologies (GXV-T) programme will include Honeywell's VR instrument panel to replace glass windows in vehicles with AR technology. This will adapt Honeywell's near-to-eye and display technologies used in military and commercial avionics flight decks to future ground vehicles. The display system will project a wide-angle, high-definition 360-degree view of external conditions [301].	TRL 4	The display may assist vehicle operators to track optimal routes, review infrared and terrain classification views and view locations of allies and adversaries.	Low maturity technology. First virtual windows development is expected to continue in 2016.
OSG Company of Kibbutz Palmach Zova, Israel: ScreeneX touch-screen bullet-resistant windshield. The touch-screen device is inserted between the safety glass layers and the screen is connected to the vehicle's multimedia system. The products are based on a combination of glass and polymers, made via a proprietary	TRL 6	The device saves space in the crew cabin and removes cabin obstacles which can injure occupants. The screens can be used in vehicles such as HUMVEEs and MRAP, where the cabin	Opacity and usability of the embedded touch screen is yet to be verified.

manufacturing process [300].		is fitted with bullet-resistant windows.	
NASA and DARPA, US: Created a telepresence system for control of Robonaut for conducting repairs on the International Space Station or on satellites. The robotic system was demonstrated threading nuts onto bolts, knot tying and similar tasks [298, 299].	TRL 5-6		
HP: Zvr virtual reality display uses a 3D monitor, precise head tracking and digital pen technology to create virtual holographic 3D images. The user can manipulate these images to explore data in three dimensions [10].	TRL 7-8		
The major VR headset makers have now released consumer VR headsets: Oculus Rift, HTC Vive and PlayStation VR. Microsoft HoloLens presents an AR version for tele-assistance and other applications.	TRL 7-8		
Logistic Information Systems			
US Army: The Global Combat Support System – Army (GCSS-Army) was fielded to 14,000 users at 281 supply support activities across the US Army in November 2015 (Wave 1). This includes warehouses in US, overseas bases and at forward-deployed locations in Iraq and Afghanistan. Wave 2 will replace the Property Book Unit Supply Enhanced and the Standard Army Maintenance System. Future increments will incorporate other critical logistic functions including aviation maintenance, Army Prepositioned Stocks and business intelligence and business warehousing tools [304].	TRL 8-9	With GCSS-Army, finance and logistics are being linked for the first time, enabling near-real-time management of inventories and finances.	
US DoD: Logistics Modernisation Programme (LMP) went live in 2003 with phased roll-out and the legacy systems were finally retired in 2014. It is one of the world's largest integrated supply chain, maintenance, repair and overhaul planning and execution solutions. It uses SAP commercial software to manage and track orders and delivery of materiel. LMP handles approximately two million transactions per day and manages $22 billion in inventory with tens of thousands of vendors. It has 30,000 users at over 50 locations and interfaces with over 70 DoD systems. LMP generates demands from units and depots and these get to contractors either from contracting commands like TACOM or from the Defense Logistics Agency (DLA) [304].	TRL 9	SAP's COTS products are used to streamline the business processes associated with the planning, acquisition, supply, maintenance, repair and overhaul of weapon systems, spare parts and services to the soldier. Various SAP modules are used, configured and code-extended in accordance with SAP-sanctioned software extensions in order to deliver specific functionality. Overall customisation in the LMP solution consists of 29 SAP modifications of the	This is a very large and complex system that required phased roll-out and development over almost 20 years. Additional requirements emerged that required second iteration of the LMP: e.g. shop floor automation within the US Army's organic industrial bases, and enterprise equipment management.

		COTS products.	
US Army: LOGSA Information Technology Services is an AMC contract program that (among other things) runs the US Army's Logistics Information Warehouse (LIW). This database collects large volumes of data generated internally and provides logistics and business analytics services to over 65,000 US Army users. The US Army currently uses an on premise IBM Hybrid Cloud based at AMC headquarters in Redstone Arsenal, Alabama, to run the system [304].	TRL 9	The analytics are used to integrate information on materiel, including readiness, force structure and the state of repair of equipment.	The option of using commercial cloud is currently off the table due to security considerations.
US RDECOM: Developing a Configured Load Building Tool (CLBT) hat will build multiclass cargo loads configured for any consumer on the battlefield in any configuration. The tool is expected to be compatible with all material handling equipment, cargo platforms and tactical conveyances with use of a generic algorithm to determine the best load plan and a strapping algorithm that uses mathematical analysis of forces exerted on the load [151].	TRL 5-6	Enabling rapid validation of uniform loads for conveyance; incorporation of hazard classification; decision support for correct strapping, blocking and bracing; support to automated material handling operations [151].	Tool not yet developed.
US RDECOM: Designing an ammunition management system of record that will provide depot storage optimisation layouts and real-time cost/benefit analysis for storage planning [151].	TRL 5-6	Reduced labour requirements; increased depot storage density; improved estimation of re-warehousing labour costs; reduced re-warehousing costs [151].	Tool not yet developed.
ONR/USMC, US: Developing the Shipboard Cargo Flow Tool (SCFT) to supplement and orchestrate existing Adaptive Logistics Planning System – Marine Corps (ALPS-MC) and Integrated Computerised Deployment System (ICODES) services. SCFT leverages the ICODES Service Oriented Architecture platform to accelerate development and transition into service.	TRL 5-6	SCFT is expected to help further develop and refine sea-basing concepts. It provides the capability to plan, assess and execute an intra-hull offload plan for a sea base to support landing and distribution plans produced by ALPS-MC. It may also incorporate supply, on-load and other activities.	
US DoD: Using the Fleet Insight Toolkit (FIT) – an advanced web application that turns wheeled vehicle usage and health data into actionable information for unit maintenance. It aggregates related wheeled vehicle logistics data from multiple sources and from Digital Source Collector (DSC) to help exploit the currently available CBM+ data. It maintains interfaces with the Logistics Support Activity (LOGSA) Integrated Logistics Analysis Program (ILAP) [305].	TRL 8-9		
UK MoD: Using Logistic Functional Area Services (LogFAS) capability (and its new version LogFS) which provides a suite of	TRL 8-9		

logistic tools and applications used by NATO countries to satisfy capability requirements for planning and execution and sustainment during deployment [305].			
Canadian Armed Forces (CAF): A sense-and-respond logistics decision support capability prototype has been designed to handle dynamic complex SCM distribution problems, enhance supply chain visibility, optimise the supply chain, provide shared situation awareness, self-synchronisation and faster speed of execution [305].	TRL 8-9		

Appendix G Horizon Scan of Health Technologies

Examples	TRL	Applications and Benefits	Challenges and Barriers
CASEVAC			
US DoD: REV and REX marsupial pair - REV (Robotic Evacuation Vehicle) is a robot version of an ambulance that carries REX (Robotic Extraction Vehicle). REX is a small stretcher bearer that drags soldiers into the safety of the ambulance. REV has a life-support pod with flat-screen TV facing the wounded soldier's face for communication [15].	TRL 6	Use of unmanned systems for search and rescue operations removes other personnel from danger and extends the areas that can be searched.	Robustness of communications remains a limitation, especially in areas where line-of-sight communications cannot be guaranteed. A significant amount of R&D is required to make the systems tactically useful.
DARPA: ATLAS project with Boston Dynamics looks at developing a biped robot for search and rescue [307].	TRL TBC		
The Battlefield Extraction Assist Robot (BEAR) is a CASEVAC robot that can carry a person to safety [308, 404].	TRL6		
Immediate Casualty Management			
US Marine Corps Futures Directorate: Working on technology to deliver life-saving care within an hour of catastrophic injury, regardless of location. During the Rim of the Pacific Exercise 2014, a small vehicle was used to provide shock trauma care at the company level. The exercise was also used to demonstrate use of telemedicine, with sensors used to monitor and transmit a patient's vital signs to a remotely located doctor. By 2016, it is planned to incorporate unmanned aerial vehicle resupply and a robust surgical capability into future exercises (Class VIII Delivery UAV).	TRL 6-7	This technology use is part of the directorate's latest concept of operations – Expeditionary Force 21, with emphasis on sea basing and fast, dispersed operations with more agile forces.	Incorporation of unmanned systems is yet to be demonstrated.
Case Western Reserve University, US: Developed a sprayable foam made of modified chitosan, a biopolymer derived from the shells of shrimp and other crustaceans that is already being used in other types of non-foam wound dressings. In tests on pigs, the spray reduced blood loss by 90% [309].	TRL 6	Improved treatment of traumatic injuries, particularly non-compressible injuries of the abdomen - currently no adopted method for first responders to stop this type of bleeding.	Trials on humans yet to be completed.
Swinburne University of Technology, Australia: A new type of bandage using a nanofiber mesh is being developed to draw out bacteria and speed healing [405].	TRL 5	Useful for battlefield would treatment, and wound treatment more generally.	So far, the bandage has been trialled on tissue engineered skin models. Trials in animals and humans yet to be undertaken.
University of British Columbia, Canada: Created self-propelled particles, able to travel against blood flow to deliver coagulants. The	TRL 4-5	Improved treatment options and outcomes for battlefield	Results have been confirmed in two animal models; human trials yet to be

particles use carbon dioxide bubbles as a propellant [310].		casualties/trauma. The particles proved effective in stopping bleeding even in modelled catastrophic events such as damaged femoral artery.	considered.
Case Western Reserve University, US: Internal bleeding in the lungs of soldiers resulting from explosions can lead to death. Researchers previously involved in developing artificial platelets [406] have paired clot-promoting (haemostatic) nanoparticles with a corticosteroid to help stop inflammation to produce a drug that may help reduce internal bleeding in the lungs of soldiers that experience such blasts, and internal bleeding following a traumatic event more generally. Researchers report that injecting this nanoparticle solution helped reduce lung damage in rats experiencing such trauma. The rats experienced increased oxygen levels, and reduced internal bleeding and cellular damage in the lungs [311, 312].	TRL 5-6	Options for immediate treatment of internal bleeding in the lungs are limited. This potential treatment, if administered immediately after a blast, clearly has the potential to save lives.	No mention of side-effects, or storage/transport requirements of such a drug. Human trials yet to be completed.
Robotic Surgery			
Intuitive Surgical: The Da Vinci robot is commonly used for prostate, gynaecological, head, neck and complex hernia repairs [313]. It is now the most common robotic equipment in surgeries with hundreds of thousands of surgeries performed every year worldwide [314].	TRL 8-9	For example, where heart bypass surgery normally requires opening a patient's chest, the da Vinci robotic surgical system can perform this operation using three or four 1 cm incisions in the chest. This helps with less tissue damage and faster recovery.	The machine costs about $3 million and each surgery is between $8-10K [313].
Children's Sheikh Zayed Institute for Pediatric Surgical Innovation: Smart Tissue Autonomous Robot (SMART) was designed to stitch up tissue. It is based on a standard robotic arm equipped with suturing equipment plus smart imaging technologies to allow tracking moving tissue in 3D and with equivalent of night vision. Sensors were added to help guide each stitch and be able to judge how tightly to pull. Fluorescent markers on the tissue guide the arm to the right location [315].	TRL5	Small tests using pigs shows the robotic arm performing as well or a bit better than human surgeons in stitching together intestinal tissue, although some mistakes happened when suturing inside living animals.	At this stage, the surgeons are still expected to supervise and complete the procedures
University of Pittsburgh Medical Centre: Flex Robotic System is a snake-like robot used to perform throat surgeries with better accuracy than human surgeons. It 'snakes' its way to any place in the body and causes less damage to soft tissues [314].	TRL 7	Reducing damage to tissues during surgery.	Human supervision still required.
Medrobotics: Flex Arm robotic surgical system lets surgeons operate	TRL 7	The Flex Arm robot is very easy to use,	The surgical robots have limitations in

through non-linear winding paths via a single-site access into the body. The endoscope has numerous mechanical links with concentric mechanisms. Each mechanism can be placed into a rigid or limp state. With use of 'follow-the-leader' movement with alternating rigid or limp states, it is possible to direct the endoscope into any shape through the relative orientations of its linkages [314].		with approximately 20 minutes training required (even for non-surgeons). The system may some-day allow military medics to perform minimally invasive surgery in the field [314].	what they can be used for. For example, they couldn't be used to remove a very large tumour due to the large size of the hole.
Florida Hospital Nicholson Centre in Celebration: Successfully tested lag time created by the Internet for a simulated robotic surgery in Ft. Worth, Texas (approximately 1,200 miles away) with the surgeon at the virtual controls [314].	TRL 6	Remote surgery capability will enable surgeons to attend to patients in isolated and remote areas.	Within a short period of time hackers demonstrated ability to hack a robotic surgery procedure.
Stanford University, US: Accuray CyberKnife Robotic Radiosurgery System was developed in 1990. It was approved by FDA in 2001 for treating tumours anywhere in the body [314].	TRL 9	CyberKnife has been used on approximately 40,000 patients worldwide.	Specific application.
Children's National Health System in Washington, US: Developed the Smart Tissue Autonomous Robot (STAR) that uses 3D imaging and precise force sensing to apply stitches with submillimeter precision. It is based on an industrial robot equipped with several customised components such as a force-sensitive device for suturing and a near-infrared camera for imaging soft tissue in detail when fluorescent markers are injected [407].	TRL 5	When tested in living pigs, the system was demonstrated to be more accurate than human surgeons. This is the first system that is not remotely controlled and manipulates soft tissue. Examples of potential applications include hernia operations and repairs of torn muscles.	It is expected that a surgeon would still oversee the robot's work and take over in an emergency (such as unexpected bleeding).
VascuLogic LLC: Automated Venipuncture image-guided robotic device for finding and assessing candidate veins, inserting needles, and drawing blood or delivering fluids [185, 316].	TRL 8-9	Progress toward autonomous healthcare, including for tactical combat health support. Claims to be safer, more accurate and more efficient than a human. Controllable via tablet, meaning tele-control is possible.	Cultural acceptance
Virtual Incision Corporation: A miniaturised surgical robot that can be placed entirely within the abdomen for surgical procedures relating to the bowel and colon [317, 318].	TRL 5-6	This robot does not require a dedicated operating room or specialized infrastructure, and is likely to be less expensive than existing robots. The system could enable a minimally invasive approach to procedures performed in open surgery today.	Yet to pass an in-human feasibility trial. Limited to specific abdominal procedures at this stage.
Worcester Polytechnic Institute, US: Developing Magnetic Resonance Imaging (MRI) compatible robotic surgery tools for use within MRI machines. Their system isn't made of metal, but instead has plastic parts and ceramic piezoelectric motors that allow it to work safely	TRL 5	Minimally invasive surgery guided by real-time scans from an MRI machine. Metallic robots or robots with metallic parts are not capable of being operated	Human trials are underway to assess feasibility of using robot assisted prostate biopsies, but thus far the biopsies are still carried out by hand.

inside an MRI [408].		within an MRI due to the intense magnetic fields.	
Diagnostics			
Harvard Medical School, US: Developed a new test, dubbed VirScan to test for thousands of past and current infections simultaneously. The test references a library of almost a hundred thousand synthetic protein fragments, each representing a section of a virus that an antibody may recognise. When the proteins are added to a drop of blood, antibodies attach to matching fragments. They can then be isolated and identified [325].	TRL 4-5	Applications in research, as the test enables comparison of viral histories between different groups of people. Observations based on the test may inform future vaccine development. It is expected that the test won't cost any more than the existing single-pathogen tests. Administered on a regular basis, it can help pick up viruses like hepatitis C, which people often do not know they have [325].	It is yet to be proven that the viral history generated by the test is comprehensive; some infections may be missed. Not yet commercialised.
Oxford Nanopore, France: Developed a variant of the Oxford next gen sequencer (MinION) that is small enough to run on a USB connection. It has been adapted to detect all gene sequences in a blood sample, remove the human genes and leave all pathogen sequences for analysis [321] [322].	TRL 7	Very rapid genetic sequencing on demand. The researchers seek to reduce errors through use of multiple reads.	Processing speed, reagent availability, data analysis and peripherals are yet to be developed to the point where it can be used for point of care testing. Accuracy remains a key concern with some researchers claiming they are only getting 65-80% accuracy with the device.
Biomeriex, US: Developed the BioFire multiple PCR film array that integrates sample preparation, amplification, detection and analysis with one-hour turn-around time for results. It now has four FDA-approved panels: Respiratory Panel, Blood Culture Identification Panel, Gastrointestinal Panel, and Meningitis/Encephalitis Panel. In total, these tests for over 100 pathogens [409].	TRL 7	Fast turn-around time. The small test unit can be operated by a technical assistant or paramedic and may be suitable to use in a patient transport vehicle or plane. Suitable for use in isolated areas and communities.	
McMaster University, Canada: Developed the world's most sensitive test to detect infectious diseases - a molecular device made of DNA that can be switched 'on' by a specific molecule of their choice - such as a certain type of disease indicator or DNA molecule representing a genome of a virus—an action that leads to a massive, amplified signal which can be easily spotted. It can detect the smallest traces of metabolites, proteins or fragments of DNA. The test is as much as 10,000 times more sensitive than other detection systems [323].	TRL 4-5	More sensitive, quicker, easier detection of pathogens/proteins. May eliminate the need for bulky test equipment.	Test is yet to be moved onto a paper surface to create point-of-care tests.

Harvard University, US: Showed that a new, commercially developed rapid diagnostic test for Ebola virus performed at bedside was as sensitive as the conventional laboratory-based method used for clinical testing during the recent outbreak in Sierra Leone [410].	TRL 7-8	Rapid, low cost, portable diagnosis - not having to rely on laboratory testing of samples.	This specific test/diagnostic capability is not yet extended to diseases other than Ebola.
Rutgers University, US: Created a microfluidics 'lab-on-a-chip' device that is inexpensive and can perform medical tests many times more inexpensively than conventional lab-based tests [324].	TRL 7-8	The size, cost, automated nature and portability are attractive from a deployable health diagnostic capability perspective. Sensitivity and accuracy are comparable to benchtop instruments.	
Los Alamos National Laboratory, US: Developed a portable 'battlefield' MRI system that doesn't require casualties to be transferred to large hospitals before MRI imaging can take place. The machine makes use of 'ultra-low' magnetic fields, on a par with that of the Earth, and use extremely sensitive magnetometer devices to detect these weaker signals. Hence, they also do not require nearly as much power or the supply of cryogens to keep the magnets operating [326].	TRL 5	Overcomes limitations of previous attempts, which suffered from poor image qualities and long imaging times, and an impractical need to operate in an environment almost totally isolated from ambient electromagnetic noise. A second iteration is currently being built, to improve on the first proof-of-concept. Low power requirements, lightweight.	Currently, the coils used in the new design for shielding only compensate for the Earth's magnetic field. The team is working on enhancing shielding to cancel out additional interference.
Peek Vision: Portable Eye Examination Kit (PEEK) adds a lens adapter to the smartphone's camera. Health care workers in remote locations can then use the phone to scan a patient's retina for disease and to check for cataracts. Associated smartphone apps can be used to test the patient's vision [319].	TRL 7-8	Readily available, inexpensive adapter that can be linked in to a telemedicine advisory system.	Assessment by a medical professional is still required.
Cellscope: Oto turns an iPhone into an otoscope that uses the phone's camera to view the eardrum at high magnification. With the home version, parents can send images of their children's eardrums to on-call clinicians to diagnose middle-ear infections. A pro version allows doctors to share images with their patients [319].	TRL 7-8	Bypasses the requirement to attend a GP clinic for what is a common complaint in children.	Assessment by a medical professional is still required.
AliveCor: AliveCor Heart Monitor allows a patient with a heart condition to collect a personal electrocardiogram. While the patient touches electrode-carrying sensors attached to the phone's case, an associated app displays the patient's heart rate and flags irregular rhythms known as atrial fibrillations. The app also transmits data to	TRL 7-8	Allows for more frequent monitoring of high-risk patients and early detection of problems.	Assessment by a medical professional is still required.

the patient's doctor [319].			
Health-state Monitoring			
US Army Medical Research and Materiel Command: Developing physiological sensors that soldiers can wear for remote monitoring [411].	TRL 5-6	Potential applications: health state monitoring, adjusting water and calorie intake, automatic casualty triage [411].	
University of California, US: Developed the Chem-Phys patch capable of monitoring both biochemical and electric signals in the human body. It records electrocardiogram heart signals and tracks levels of lactate (marker of physical effort). The device is worn on the chest and communicates wirelessly via smartphone, smart watch or laptop [328].	TRL 4	Potential applications include monitoring athletes, and monitoring patients with heart disease. This type of wearable device can alert users to health problems such as fatigue, dehydration and dangerously high body temperatures.	Further research will look at adding sensors for other chemical markers such as magnesium and potassium, and monitoring other vital signs.
University of Illinois, US: Developed Biostamps - circuits that act like skin (stretchy, flexible), collect power wirelessly (powered by Near-Field Communication radio signals), and can be worn almost anywhere on the body. Different functions then require different sensors. Examples include monitoring UV exposure, using sensitive dyes to detect chemicals in sweat, or electronically measuring blood pressure. Other potential applications include measuring skin hydration, mental stress, wound healing (through temperature and heat flow) and biostamps for delivering drugs through the skin. The stamps can contain hundreds of thousands of sensors, as well as resistors, LEDs, and a radio-frequency antenna. A reusable version has also been developed that has energy storage, memory, many sensors, Bluetooth communication, as a means of more rapidly developing new sensors for new applications and for more rapidly trialling. Sensors are about to enter clinical trials in the US and Europe. Units that communicate with Android smartphone are available, although units with embedded biosensors have not yet been made available to the public at large [329].	TRL 6-7	Nearing commercial viability. Wearable, non-invasive, do not require a physically attached power source, can replace existing practice of tests at a check-up or at presentation of symptoms. Also allows earlier detection of possible problems, and health prognostics. Smaller, cheaper health monitoring on the battlefield or during tactical/strategic CASEVAC. Costs tens of cents when manufactured on a large scale. Waterproof and breathable.	Yet to undergo clinical trials. Does not store energy (doesn't really need to), but stretchable batteries and supercapacitors have already been built and tested.
Examples of biometric gadgets worn by elite sportspeople include [327]: **Readiband**: Electronic wristband that measures sleep quality and quantity, which can help predict a player's reaction time for the next day. Coaches can use an associated online tool to monitor the sleep patterns and fatigue of professional athletes. Data is processed by the	TRL 8-9	Monitoring of training and physical performance of soldiers. Improved training outcomes, including the ability to detect physiological problems earlier, and to produce custom training regimes to address areas of weakness.	The more advanced systems are expensive (e.g. US $22,800 per year for 20 Readibands, including analytics software (individual wristbands are not sold). The utility across all soldiers may be limited.

SAFTE model (Sleep, Activity, Fatigue, Task and Effectiveness) developed by the US Army. **Motus Sleeve**: A compression sleeve with sensors that tracks a baseball player's throwing motions. Pitchers who use the sleeves to correct their technique may be able to prevent ulnar collateral ligament injuries, which have resulted in an epidemic of reconstructive procedures. An alternative to motion capture imaging. **Myontec Mbody Pro**: Compression shorts with sensors that measure muscle imbalances in the legs. The garment can determine, for example, whether athletes are favouring one leg or are using their quadriceps disproportionately compared with their hamstrings. The feedback can help athletes improve their technique and possibly forestall cramps or injuries. **BSX Insight**: A compression sleeve worn on the calf that measures lactate threshold—the level of exercise intensity above which lactic acid builds up in the bloodstream, causing discomfort and forcing the athlete to slow down. Normally, monitoring lactate threshold requires multiple finger-prick blood samples, which must be sent to a lab. This non-invasive sensor, however, can be worn while working out. **OptimEye S5:** This device's sensors precisely record a player's movement on the field or court. The device, which sits over the upper back inside a compression garment, monitors acceleration, deceleration, change of direction, jump height, and distance travelled, among other metrics. Coaches use the data to keep tabs on how hard players are working and to prevent injuries resulting from overtraining. Used by nearly half of the NFL, a third of the NBA, more than 100 NCAA teams, half the English Premier League, and dozens of other professional hockey, soccer, rugby, and rowing teams around the world.		Particularly applicable to special forces.	
Advanced Prosthetics			
University of Washington, US: US mechanical designer Ivan Owen has produced 3D-printed had prosthesis inspired by an 1845 design developed in Adelaide. He has made his designs freely available. Over 1600 people have now received the 3D-printed hand prosthetics at low cost [331].	TRL 7-8	Low cost and freely available design makes the prosthetic easy to obtain and to develop further.	Availability of 3D printers is still low in poorer countries. Medicolegal constraints may need to be addressed for wide-spread adoption.
Johns Hopkins Applied Physics Lab: Successfully replaced a patient's	TRL 6-7		

arms with modular prosthetics controlled by the patient's thoughts. Achieving ability to move objects and perform other complex actions required him 10 days of training and practice [10].			
Scientists have demonstrated an ultrathin silicon nanoribbon that incorporates sensors for detecting strain, pressure, temperature and humidity. This material could be used to create artificial skin for prosthetics [10].	TRL 4	A step towards prosthetics with functionality that is close to the original limbs.	Enabling technology demonstration; actual use in prosthetics has not yet been demonstrated.
Caltech, US: By implanting neuroprosthetics in a part of the brain earlier in the movement pathway (not the part that controls not the movement directly but the part related to intent to move), researchers have developed a way to produce more natural and fluid motions [332, 333].	TRL 7	For amputees controlling robotic limbs, this has shown more natural and fluid motions, greater versatility of movement.	Clinical trials in humans are underway.
Advanced Manufacturing			
US Armed Forces Institute of Regenerative Medicine (AFIRM): Developing technology for 3D bio-printing skin cells for burns injuries. The device (similar to an inkjet printer) uses cartridges with two types of skin cells – fibroblasts and keratinocytes. After constructing a 3D map of the injury, the computer tells the printer where to start printing and what type of cells to use, depending on the depth of the injury [220].	TRL 4	3D bio-printing is currently being researched for extremity injury and skin, genitourinary and facial repair.	The technology is yet to be translated into clinical use. Larger commercialisation audience is required for the technology to be self-sustaining without DoD funding.
Cornell University: Bioengineers have successfully printed human ears for transplantation [218].	TRL 6		Bio printing is still in early days, with some promising results
Orthopaedic surgeons are starting to use 3D printing to build bone replacements. This includes thousands of 3D printed replacement parts for hips, knees, ankles, parts of the spine, and sections of the skull. Most are titanium implants. In the US, several printed, custom implants have received FDA clearance, including total knee replacement and craniofacial plate [334].	TRL 9	Biggest benefit is the ability to design implants that are specific to an individual's patient's body (using data from MRI or CT scans). This is particularly useful for parts with complicated geometries such as pelvis.	Custom implants are not yet wide-spread. For market leader Arcam, less than 1% of the implants manufactured on the electron beam melting machines are patient-specific. Test and evaluation remains an obstacle for customised parts.
Queensland University of Technology, Australia: 3D printing of mechanically reinforced, tissue engineered constructs for the regeneration of body parts. This was done by reinforcing soft hydrogels by a 3D printed scaffold, mimicking a process that occurs often in nature, and producing a material with stiffness and elasticity are close to that of cartilage [335].	TRL 4	Overcomes the problems of hydrogels alone, which have excellent biological properties but cannot meet the mechanical and biological requirements for tissue regeneration of the musculoskeletal system.	Low TRL. Practical use yet to be demonstrated.
Institut de Recherches Cliniques de Motreal, Canada: Created an	TRL 7-8	Improved control of diabetes. Opening	Partial solutions are being rolled out

artificial pancreas enabled by advances in multiple technology areas (sensors, actuators, algorithms, and 'synthetic' insulin). The device is a closed-loop autonomous system that monitors blood-sugar levels and reacts accordingly by controlling an insulin pump. The device is also able to anticipate changes in blood-sugar levels using 'big data' analytics and learning systems that adapt to individual patients [412].		the way for improved health outcomes using this type of data analytics/machine learning technology for conditions other than diabetes.	already; the full closed-loop system is undergoing clinical trials. Focus is on diabetes, not directly applicable to what would normally be considered health issues induced through involvement in Defence.
MIT, US: (with DARPA funding) Created a small, portable device for flow processing manufacturing. Currently, the system can produce four drugs formulated as solutions or suspensions: Benadryl, lidocaine, Valium and Prozac. Up to 1000 doses of a given drug can be manufactured in 24 hours. Continuous system is based on development of chemical reactions that happen as reactants flow through small tubes. The reactions can take place at temperatures up to 250 degrees Celsius and pressures up to 17 atmospheres, in the first module. In the second module, the crude drug solution is purified by crystallization, filtered, and dried to remove solvent. It is then dissolved or suspended in water as the final dosage form. An ultrasound monitoring system ensures correct drug concentration in the solution [336].	TRL 5-6	The system can give greater flexibility in responding to demand surges. By swapping in different module components, the researchers can easily reconfigure the system to produce different drugs, switching from one compound to the other within a few hours. It is useful for making 'orphan drugs' and for use in regions with few manufacturing facilities.	The developed system can make four different compounds. The researchers are now working on the second phase of the project, aiming to make the system 40% smaller and able to produce more complex drugs, including in tablet form.
Genetic Manipulation			
CRISPR-Cas9 is a promising biological tool that allows investigation and manipulation of genes inside cells with unprecedented precision. A new improvement (CRISPR interference method) also allows use to modify genomes of induced pluripotent stem cells [354].	TRL 5-6	This is predominantly a tool for research at this stage. CRISPRi is more efficient that CRISPR with 95% of cells created showing gene suppression (compared with 60-70% for CRISPR-Cas9 method); it also did not cause any off-target changes. This may facilitate study of genetic diseases and identification of new therapeutic targets.	Risk of inappropriate use; specific ethical questions around genetic manipulation. Chinese researchers have recently revealed use in modification of human embryos.

Appendix H Updated Rapid Technology Assessment Framework

The Rapid Technology Assessment Framework (R-TAF) was originally developed as a CSS-centric decision-support framework to assist in identifying promising technologies [7]. Recent changes relate mainly to the sub-questions for question 2: Is the new technology better than the current solution? Whereas the original form drew mainly on doctrinal wording, the current form reflects the key technology discriminators identified during subsequent Army Logistic SME workshops.

The updated version is presented below: it consists of the three key questions and associated sub-questions that are applied to the selected technologies. The first set of sub-questions is supported by three checklists: A) Enduring logistic effects, B) Desired technology effects, and C) Desired technology characteristics. Checklists B and C take into account common parameters across a range of operational environments. Additional considerations include the quality of available information. Barriers to adoption are considered within question 2.

1. Is the new technology useful to CSS? - Does the new technology enable enduring logistic effects? – ref. *Checklist A* - Does it achieve desired effects for expected and extreme operational environments? – ref. *Checklist B* - Does it have the desired characteristics for expected operational environments? – ref. *Checklist C*
2. Is the new technology better than the current solution? - Does it offer additional force protection? - Does it improve delivery of CSS? - Does it entail specific points of vulnerability? - What are the cross-domain effects?
3. What is the cost involved? - What is the maturity of the technology? - What are the expected acquisition and maintenance costs? - What are the integration considerations? - Is it compatible with current projects and concepts of operation?

Checklist A: Enduring Logistic Effects

Supply

- Demand forecasting
- Inventory management and provisioning
- Procurement
- Warehousing
- Disposal of materiel
- Waste disposal and management

Movements and Transport
- Preparation and planning
- Terminal operations, including loading, unloading and cross-loading
- Distribution: transport of personnel and materiel

Materiel Engineering and Maintenance
- Control of design, inspection, testing
- Condition monitoring, calibration, servicing
- Classification as to serviceability/engineering certification
- Overhaul
- Modification
- Repair
- Rebuilding
- Reclamation
- Recovery
- Salvage/cannibalisation
- Evacuation

Infrastructure Engineering and Maintenance
- Vertical and horizontal construction: planning, constructing and maintaining infrastructure
- Provision of essential services
- Obtaining resources in theatre
- Waste disposal and recycling

Personnel Support Services
- Personnel administration
- Postal services
- Welfare services
- Management of prisoners of war
- Messing
- Accommodation
- Catering
- Laundry
- Shower services
- Support to mortuary affairs

Health Services
- Casualty prevention
- Casualty treatment
- Casualty evacuation

Command and Control (C2)
- Logistic intelligence analysis in support of the Common Operating Picture
- Maintaining situational awareness
- Business intelligence and modelling for decision support

- Tactical/operational/strategic planning
- Tactical/operational/strategic communication
- Control and coordination of specific logistic functions through Logistic Information Systems (LIS)
- Development, application and measurement of doctrine, policy, structures, processes
- Contract management

Capability Life-Cycle Management

- Identifying capability gaps
- Defining capability requirements
- Acquiring and integrating capability
- Managing fleet in service: rotation, deep maintenance, modification, monitoring fleet health status
- Disposal of capability

Checklist B: Desired technology effects for expected and extreme operational environments

Supply

- Reduce stockholding and resupply requirements
- Reduce dependence on limited transportation platforms
- Facilitate force self-sustainability
- Facilitate rapid surge capability
- Reduce dependence on global supply chains
- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance/augment human capability
- Enable distributed, in situ generation of sustenance, power and energy
- Reduce dependence on global supply chains for Classes 1 and 3

Movements and Transport

- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance human capability
- Facilitate distribution in urban, amphibious and littoral environments

Materiel Engineering and Maintenance

- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance human capability
- Facilitate access to specialist support
- Reduce maintenance requirements

Infrastructure Engineering and Maintenance

- Improve robustness of critical infrastructure and systems
- Provide power and energy as well as other key services in a distributed manner
- Reduce reliance on ICT connected systems for essential services
- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance human capability
- Facilitate access to specialist support

Personnel Support Services

- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance human capability

Health Services

- Extend evacuation options and time windows for casualties
- Replace humans where possible, especially for dangerous and traumatic tasks
- Replace humans for specialist tasks
- Enhance human capability
- Facilitate access to specialist support
- Facilitate prevention, diagnosis and treatment of psychological trauma
- Facilitate detection, identification, protection and treatment in relation to hazardous substances
- Facilitate cross-exposure control measures
- Reduce personnel exposure to environmental extremes

Command and Control
- Maintain or improve situational awareness through gathering, transmission and analysis of data
- Facilitate tailoring of logistic effects
- Facilitate decision support for strategic/operational/tactical planning and C2
- Enable communication across extended distances
- Facilitate preparedness for deployment
- Enhance human capability
- Facilitate data processing by operators and decision-makers
- Facilitate communication across cultural/language barriers
- Facilitate access to specialist support
- Operate in degraded network availability environments
- Facilitate communication in urban, amphibious and littoral environments

Capability Life-Cycle Management
- Maintain or improve situational awareness through gathering, transmission and analysis of data
- Facilitate tailoring of logistic capability
- Facilitate decision support for strategic planning and C2
- Maintain technological edge

Checklist C: Desired technology characteristics for expected operational environments

Physical Characteristics
- Lightweight
- Robust to physical stress and range of environmental conditions
- Small and portable
- Rapidly deployable: easy to procure/access, pack and transport
- Easy to repair/ replace
- Distributed in nature

Functional Characteristics
- Multi-functional, flexible, adaptable
- Scalable in effect
- Incorporating redundancy and surge capacity
- Sensor-enabled and networked
- Predictive
- Working within limited bandwidth availability
- Resistant to cyber attacks

Interface Characteristics
- Designed with awareness of cultural sensitivities
- Cognisant of operator state
- Reactive to operator state
- Protective/ preventive

- Enabling of decision support and rapid response
- Standardised for joint and coalition operations
- Interoperable with a range of opportunistic platforms

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19. ABSTRACT
Strategic planning is supported by an understanding of emerging trends and technologies. This report provides such a horizon scan for Combat Service Support. Global trends and the results of science and technology literature scans across seven domains (power and energy, transportation, automated and autonomous systems, materials and manufacturing, sensors, information and communication technology, and health technologies) are presented. Technologies of interest are further assessed in terms of their usability, potential costs and comparison with the existing options. A comparison to the results of the scan of the previous year is provided, and previous recommendations updated. Finally, an analysis of emerging trends and technologies draws out new recommendations, including for ongoing horizon scanning activities to be combined with development and assessment of detailed concepts of employment for some maturing technologies that offer significant benefits for ADF Land Logistics.